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SURFACE ELECTRIC STRENGTH OF THERMOPLASTIC MATERIALS IN VACUUM

by

Stanislaw Grzybowski

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In spite of the broad use of a vacuum as an insulator, and numerous studies on the subject, there is still no single generally accepted theory for the mechanism of the development of discharges along a solid dielectric placed in a vacuum. This work systematizes and discusses the effect of some particular factors on the mechanism of discharge and on the electric strength of the vacuum-solid dielectric system. Results of our investigations form the basis of a discussion of the effects of pressure, sample length, metallization of the surface of the contact sample-electrode, and ways of conditioning the potential of flashover.

The results are given and analyzed of investigations on surface strength of thermoplastic dielectrics (polymethylmethacrylate, polytetrafluoroethylene and polyethylene) at switching and surge overvoltages, considering the time of duration of the wave front and the number of switching surges. The author presents his own mechanism for the development of discharges along the investigated materials placed in a vacuum, and derives the mathematical dependence for the flashover potential along a solid dielectric in a vacuum as a function of the time of duration of the switching surge wave front.

Studies of the mechanism for the development of discharge have been expanded by measurements of the degree of degradation of surfaces of solid dielectrics. Oscillograms on the course of consecutive switching surges are obtained and analyzed. Photographs are shown of the degradation of surfaces of the investigated solid dielectrics. They were obtained by an electron microscope, with flashovers at direct and alternating potentials.

1. INTRODUCTION

During the last two decades, there has been broader and broader use of a vacuum as an element of electroinsulation systems. Vacuum is used in electric power equipment, for instance in vacuum switches, cryogenic cables and vacuum distributors, and in research instrumentation, such as vacuum lamps, X-ray lamps, electron microscopes, accelerators, etc.

The operation of any electric equipment with a vacuum as an insulator requires a vacuum chamber, whose walls are made of some insulating material, or the construction of a passage insulator for a metallic vacuum chamber. In some vacuum systems, the high voltage cable has to be mechanically supported by a solid dielectric - spaced insulator.

A solid dielectric system between electrodes placed in a vacuum has lower electric strength than a system of two electrodes with the same gap length between them. An understanding of the jump (flashover) mechanism along the surface of solid dielectrics is of considerable scientific importance, since the surface of dielectrics is usually the weakest spot in vacuum insulation systems.

Recent years have seen many studies of the flashover mechanism along the surface of solid dielectrics in a vacuum. Studies were also made of various factors influencing the flashover potential, such as the type of insulation material, the sample shape, and the type of contact between the electrodes and the solid dielectric.

In spite of the broad use of a vacuum, and many studies in this area, there is still no single, generally accepted theory for the development of discharges along the insulation material placed in a vacuum. There is also no uniform view on the effect of particular factors upon the mechanism of this discharge, and upon the electric

strength of the vacuum-solid dielectric system.

When studying the literature in this field one can find that there are many disagreements in reported results of the studies of surface strength of solid dielectrics in vacuum performed by different investigators. The cause lies in different experimental conditions and in different ways of conditioning the samples.

One of the factors which has not been investigated more thoroughly is the dependence of the potential of flashover on the type of potential applied. There have been no studies in general with potential simulating the switching potential and there have been no studies of the effect of the number of switching surges on change of the surface strength of thermoplastic dielectrics.

Hence, at the present time, the topic of studies of electric surface strength of solid dielectrics in vacuum still remains an open topic for studies. Previous investigations involved mainly ceramic dielectrics, and there are not many works concerned with strength of thermoplastic dielectrics in vacuum. So far, some studies dealt with surface strength at the direct potential and lightning surge, and in the last years also at alternating potential. But the literature contains only a few references to works concerned with surface strength of solid dielectrics in vacuum at switching potentials [52, 53, 54, 79].

The problem of surface strength of solid dielectrics in vacuum, and particularly of thermoplastic dielectrics at switching overvoltages, has become now the most important and up-to-date problem because of the construction of vacuum electroenergetic facilities of high voltage, and particularly of cryogenic and superconducting cables [40, 66]. In those cables, vacuum forms the basic insulating medium, and solid dielectric is utilized as a support between the conducting parts [1, 41, 42, 43, 65].

In Poland studies on the problem of surface strength of discussed systems are carried out at the Wroclaw Polytechnic University and Poznan Polytechnic University. However, they are mainly concerned with electric strength of inorganic dielectrics. Habilitation work of H. Moscicka-Grzesiak [93] and some doctoral work [86, 123, 125] belong to this area. The author considered it desirable to supplement studies in this field on the premise that organic insulators find now wider and wider application, particularly in electroenergetic systems, for which the problem of strength at switching overvoltages and at high potentials is of basic importance. The present monograph deals with just these problems. 17

The aim of this work is to learn about phenomena of discharge along thermoplastic dielectrics, particularly at switching overvoltages, and to check and develop a theory of flashover in vacuum. The second aim of this work is to obtain quantitative data with regard to surface electric strength of thermoplastic dielectrics in vacuum.

The first part of this work (Chapter 2) deals with collection and classification of literature data concerning the surface strength of solid dielectrics in vacuum. On the basis of these data, a program is developed for realization of this work. Chapter 3 contains a review of theories trying to explain the mechanism of flashover along the surface of a solid dielectric in vacuum.

Next parts of this work describe the testing system and experimental procedures (Chapter 4) and contain the analysis of present investigations of the author (Chapters 5 and 6). These investigations comprised the electric surface strength of thermoplastic dielectrics (polymethylmethacrylate, polytetrafluoroethylene and polyethylene) in vacuum at the switching and surge overvoltages, the effect of the form of potential, the effect of the time of duration of the front wave, and of the number of switching surges. Moreover, the work included

also the effect of pressure and of the time and method of conditioning the samples upon the surface strength, and also degradation of surfaces of investigated samples as a function of the number of flashovers.

In the next part, Chapter 7, on the basis of our own investigations the author proposes a theory of the development of mechanism of flashover along thermoplastic materials in vacuum, including the mechanism of flashover at switching overvoltages.

Chapter 8 contains remarks and final conclusions. Appendices presenting tables of the results of investigations conclude the work.

On the assumption that there is no uniform view on the mechanism of flashover along organic dielectrics, the author makes an analysis and comparisons of literature data with the own concept of this mechanism, based on our measurements. He derives an analytical equation for the surface electric strength of solid dielectrics in vacuum, as a function of the time of duration of the switching surge wave front.

The author considers that the presented work should form a contribution to studies of systems of organic dielectric-vacuum, mainly with regard to electric surface strength at switching overvoltages. This work also supplements and provides a series of new quantitative data concerning surface electric strength of solid dielectrics in vacuum.

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2. SURFACE ELECTRIC STRENGTH OF SOLID DIELECTRICS IN VACUUM

The idea of using vacuum as an insulator originated back in thirties of the twentieth century, hence the number of investigators who carried out studies of the phenomenon of jump (flashover) between electrodes in vacuum is considerable. The results of studies have been reviewed in the works [25, 60, 61, 107].

The mechanism of flashover in the vacuum gap is not fully understood, since it is complex and its parameters are difficult to control. If we introduce a dielectric between the electrodes in vacuum, the complexity of the system will be further increased by new parameters which should be considered.

In the case of flashover along surfaces of solid dielectric one should distinguish two stages of the development of mechanism:
- appearance of free electrons,
- discharging along the surface of the dielectric.

In vacuum there is no sufficient number of free electrons to cause the flashover, hence the electrons must be supplied to the system by a mechanism of electron emission after application of high potential.

There are possible several processes of electron emission from the surface of metal, depending on temperature and potential of the electric field, and depending whether the surface is bombarded by electrons or ions. Mechanisms of the emission of electrons may be divided into the following categories:

1) field emission,
2) thermal emission,
3) field-thermal emission known as Schottky emission,
4) photoelectric emission,
5) secondary emission caused by bombardment with electrons,
6) secondary emission caused by bombardment with positive ions.

In the investigated insulation system the initiation of electrical discharge will occur only as a result of the field emission of electrons. The Schottky emission and thermal emission acquire importance only at a high temperature, usually above 1000 K, and for this reason they have no influence in practical high-voltage facilities, which usually work at normal temperature.

The fact that electrons can be torn from the surface of metals by a sufficiently high electric field has been observed by many investigators at the end of the last century.

Fowler and Nordheim [31] derived Equation (2.1) for density of the current of field emission from a cold cathode:

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$$j = 1{,}54 \cdot 10^{-6}\, E^2\, \Phi^{-1} \exp\left[-6{,}83 \cdot 10^{9}\, \Phi^{3/2}\, E^{-1}\, \theta(y)\right] \frac{A}{V^2}, \quad (2.1) \qquad (2.1)$$

where: E - electric field potential at emitter in $\frac{V}{m}$,

Φ - electron work function from cathode in eV,

$\theta(y)$ - Nordheim function.

Equation (2.1) is derived for the temperature 0 K, hence its application is theoretically justified only for pure field emissions.

R.H. Fowler and L. Nordheim admitted that their equation would be somewhat dependent on temperature, but they have not described this effect clearly [31]. The first attempt to establish the effect of temperature on the mechanism of field emission was done by M.V. Houston [63]. In his work, M.V. Houston tried to determine the change of field emission described by the Fowler-Nordheim equation as a function of temperature. The results of his investigations indicate that the effect of temperature on emission current is very small, and decreases

with the increase of field potential. Thorough investigations of the effect of temperature on field emission current were also carried out by R.H. Good and E.L. Murphy [38]. Good and Murphy expressed the emitted current in general form as a function of temperature, field intensity and work function. Hence, they modified the Fowler-Nordheim equation by taking account of the effect of temperature. They determined also the range of temperature and of field intensity for various values of the work function, at which the modified Fowler-Nordheim equation finds application.

The effect of temperature on field emission was also investigated by Little and Whitney [82]. R.P. Little and W.T. Whitney determined experimentally that the emission current is independent of temperature in the range up to 1000 K, confirming thereby the original equation of the theory of Fowler and Nordheim.

Comparison of data of various authors still leaves unexplained discordant results of studies and discrepancies between theoretical and experimental results pertaining to the phenomenon of field emission. The results of F. Llewellyn-Jones and D.J. Nicholas [83], who studied the effect of temperature on field emission current, may serve as an example. Results of studies at temperature 197 K and 298 K give different values of the emission current than those expected from calculations according to the Schottky theory. But the measured values of current show a reasonable agreement with calculations according to the modified Fowler-Nordheim equation.

Therefore it may be stated that the mechanism of electron emission from the surface of metal at normal temperature is not yet thoroughly known. Since electron emission is the basic phenomenon in the process of flashover in a vacuum gap, in consequence the mechanism of flashover in vaccum also is not

fully known. Moreover, as was mentioned before, when a solid dielectric finds itself additionally in the vacuum gap, the number of factors affecting the process of discharge increases and the mechanism of flashover becomes more complicated.

So far, no satisfactory thory of the mechanism of flashover along the surface of solid dielectrics in vacuum has been advanced despite the fact that many investigators studied the phenomena of the mechanism of flashover, and proposed their various explanations.

It is known on the basis of experimental results that the potential of discharge along the surface of solid dielectrics depends on various factors, such as the type of dielectric, shape of investigated sample, method of conditioning, etc. These factors have been analyzed by Havley [60, 61] and Slivkova [107].

Factors which affect the process of flashover along solid dielectrics in vacuum can be defined as connected with solid dielectric, electrodes, and experimental conditions of studies (Figure 2.1).

Systematic listings of the parameters of these elements are shown in Figures 2.2, 2.3 and 2.4. These Figures contain also references to publications discussing dependence of the process of flashover on the above parameters.

Since studies of the phenomena of flashover along solid dielectrics in vacuum were carried out using different dielectrics, different types of electrodes, and various experimental techniques and procedures, comparisons of experimental results are haphazard. References listed in Figures 2.2, 2.3 and 2.4 were selected from the whole series of publications as those which provide a possibly accurate description of the effect of a given parameter on the process of flashover.

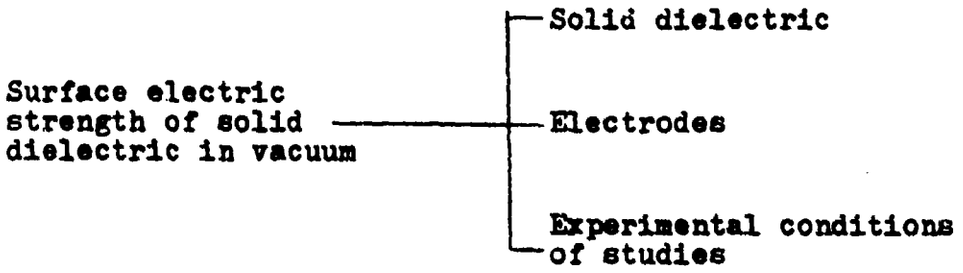

Figure 2.1. Elements affecting surface electric strength of solid dielectric in vacuum

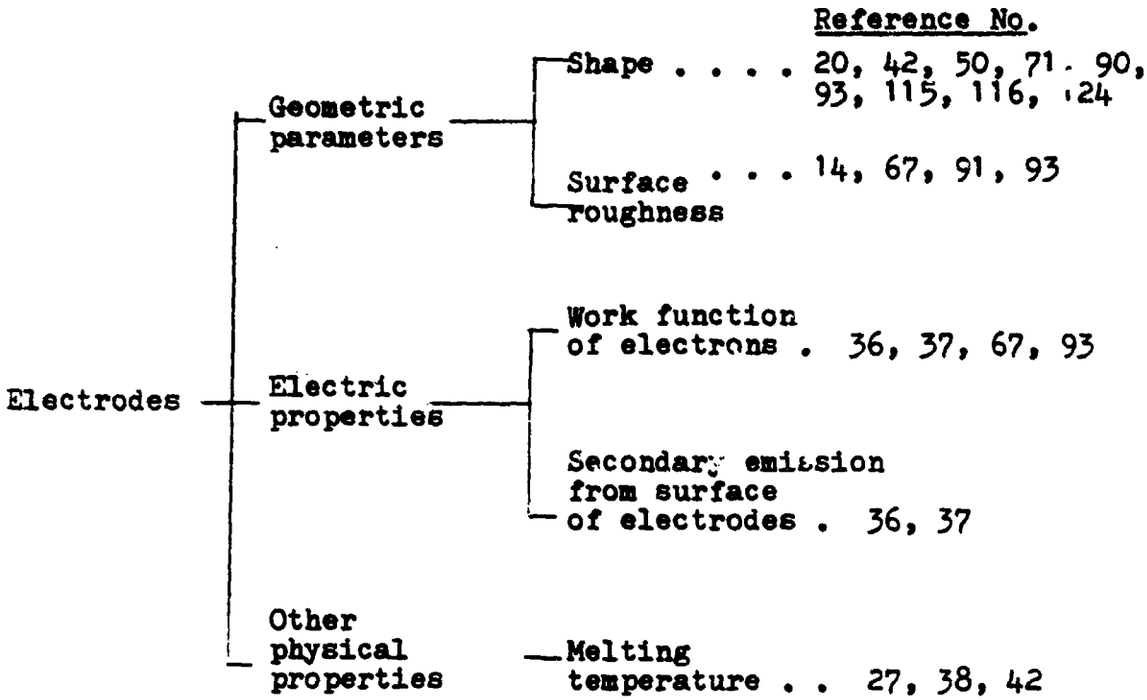

Figure 2.2. Parameters of electrodes influencing the surface electric strength in vacuum

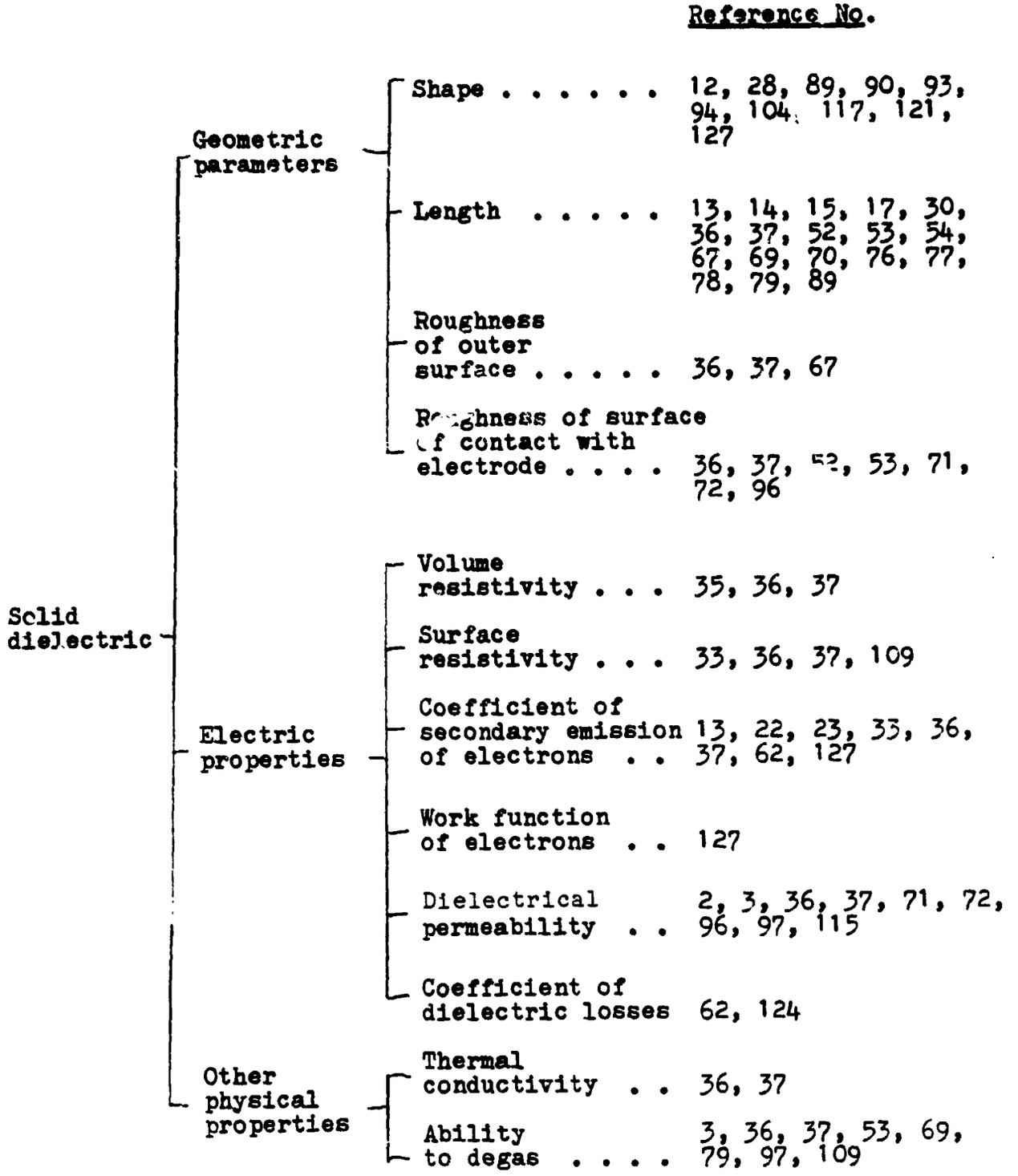

Figure 2.3. Parameters of solid dielectric affecting the surface electric strength in vacuum

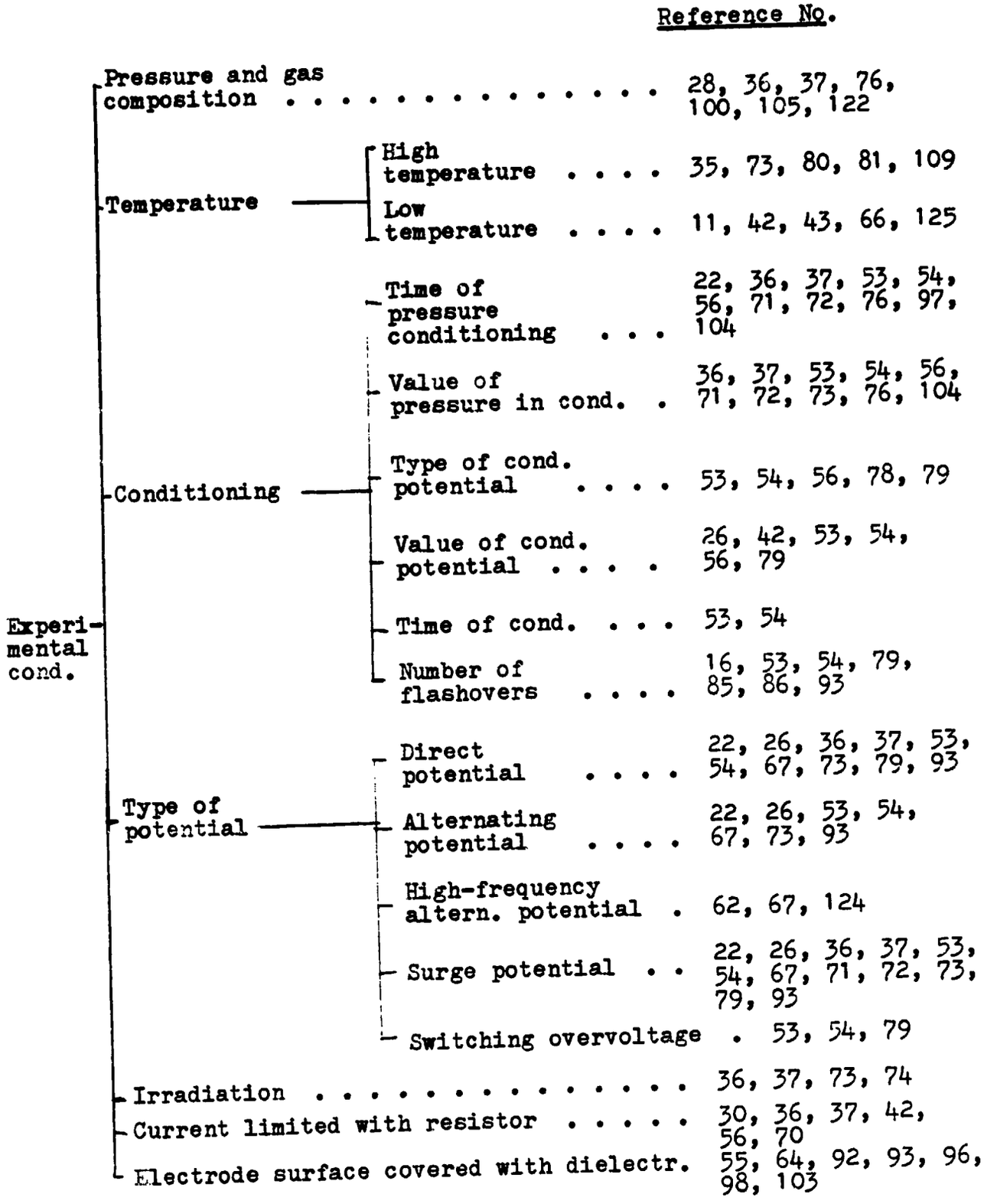

Figure 2.4. Experimental conditions affecting electric surface strength in vacuum.

2.1. EFFECT OF PROPERTIES OF SOLID DIELECTRIC ON SURFACE STRENGTH IN VACUUM

2.1.1. SHAPE OF SAMPLE

The diagram shown in Figure 2.3 lists parameters of solid dielectric which have effect upon the surface electric strength of solid dielectrics in vacuum.

The effect of the shape of samples on surface strength in vacuum at direct potential was investigated by Shannon [104], Watson [127], and later by Svinjin [117], Eastman [28], Moscicka-Grzesiak [90, 93, 94], Milton [89], and de Tourreil [121].

In those publications the investigated samples had different shapes, but the majority of investigators used samples in the form of a cylinder.

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The most thorough study of the effect of various shapes of samples on the potential of flashover was carried out by J. Shannon, S. Philip and J.G. Trump [104]. Their investigated samples were 25 mm long and had shapes shown in Figure 2.5. Values of the flashover potential of investigated samples are presented in Figure 2.6. Samples marked by symbols A_3, B_1, B_3, C_3 and C_4 had the highest electric strength, exceeding 180 kV after conditioning. The shape of these samples either provides a barrier for surface discharges, or lowers the potential of electric field at the solid dielectric-cathode junction, which causes an increase of the surface strength of the system. The highest surface strength is possessed by the sample of shape B_3.

In the case of a sample with the shape of a truncated cone, the potential of flashover changes as a function of the inclination angle of the cone, and depends on the polarity of electrodes. The obtained results of studies indicate that the sample has the highest electric strength when the base of the truncated cone is placed on the cathode.

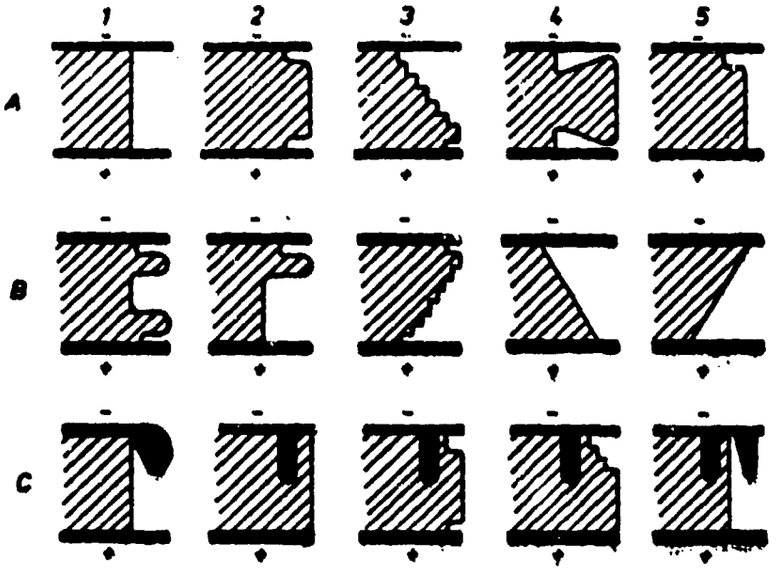

Figure 2.5. Shapes of samples 25 mm long investigated by J. Shannon, S. Philip, J.G. Trump [104] .

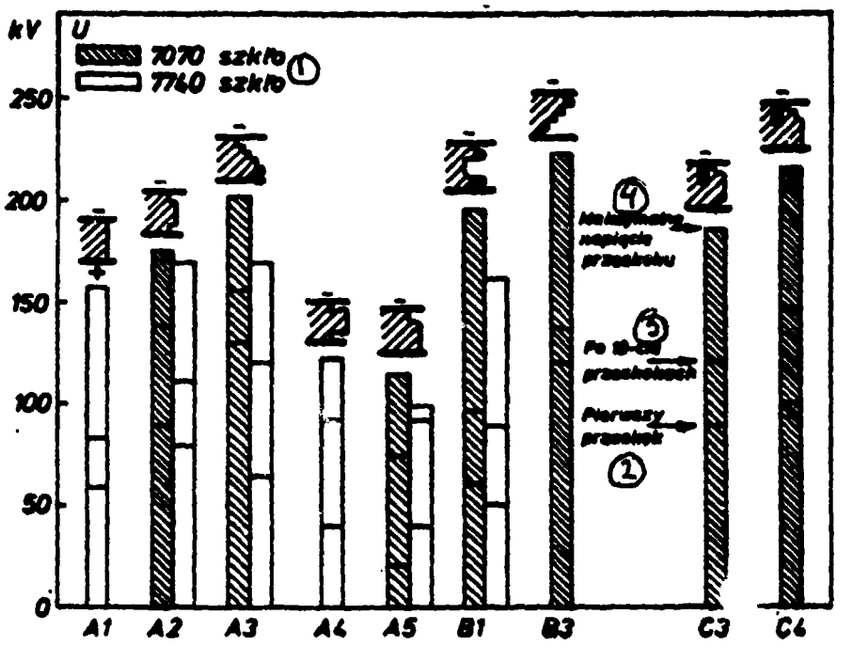

Figure 2.6. Flashover potential for samples of various shapes according to Figure 2.5. [104] . 1 - glass, 2 - first flashover, 3 - after 10 flashovers, 4 - maximal potential of flashover

Boersch [12], independently of measurements of the potential of flashover along the surface of a solid dielectric, studied the mechanism of charging of the surface of solid dielectrics in the form of truncated cone with different angles of inclination as a result of the process of secondary emission. Boersch introduced an electron beam onto the surface of dielectric through a gap in cathode. On the other hand, de Tourreil [12, 121] studied the mechanism of charging the surface through electrons emitted at the solid dielectric-cathode junction.

2.1.2. LENGTH OF SAMPLE

Similarly to the case of the flashover potential for a vacuum gap, the flashover potential along the surface of solid dielectrics does not increase linearly with increase of the length of sample. Increase of the potential is not proportional to the increase of sample length, as confirmed by many studies [13, 14, 15, 17, 30, 36, 37, 52, 53, 54, 67, 70, 72, 77, 78, 79, 89].

Figure 2.7 shows the flashover potential for various dielectrics as a function of sample length, as reported by several authors. For the purpose of comparison, the results of electric strength at direct (constant) potential were used, although at other types of applied potential the character of changes in flashover potential is similar.

The results obtained by various authors for a given solid dielectric and defined length of sample indicate considerable differences in values of the flashover potential. For example, Gleichauf [36, 37] obtained the flashover potential of 50 kV for a sample of polytetraflucroethylene (Teflon) of the length 22.5 mm, whereas the author of this work [54, 79] obtained the value of 90 kV for flashover potential also of a sample of polytetrafluoroethylene 20 mm long.

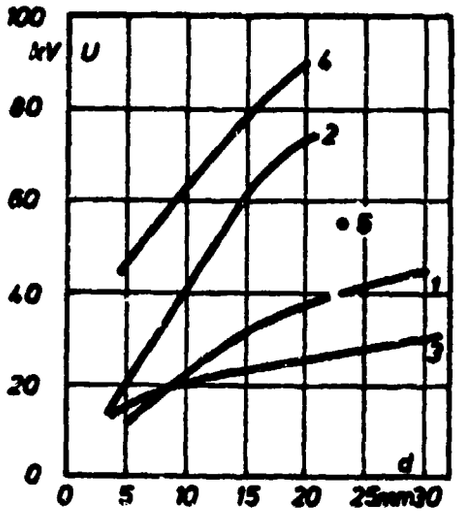

Figure 2.7. Flashover potential as a function of the length of sample at the applied direct (constant) potential: 1 - alundum (Al_2O_3) sample, according to [30]; 2 - alundum sample, according to [17]; 3 - glass sample, according to [36, 37]; 4 - Teflon sample, according to [54]; 5 - Teflon sample, according to [37].

The reported results of studies show that the length of the sample is only one of many parameters which exert effect on the value of potential of flashover along the surface of solid dielectrics. Under the given experimental conditions, the increase of flashover potential along solid dielectrics is smaller than if it was proportional to the length of sample. 16

2.1.3. ROUGHNESS OF OUTER SURFACE OF SOLID DIELECTRIC

The potential of flashover along solid dielectrics depends considerably on its outer surface. Kalyatskii and Kassirov [67] have shown that the value of surge potential of flashover for polymethylmethacrylate increases when roughness of the outer surface of a solid dielectric is increased.

The effect of surface roughness of a solid dielectric was also investigated by Gleichauf [36, 37]. The results of Gleichauf's experiments indicate that the electric strength of systems at direct potential increases by about 40% when the surface of the same dielectric is rough. He has not establish the effect of the degree of roughness on the increase of electric strength.

Further investigations carried out by Gleichauf point to the importance of localization of the area of roughness on solid dielectrics. If only a part of the surface of a glass sample was rough on the side of cathode, then the value of flashover potential increased by about 35% in relation to the value of flashover potential of a smooth sample. After the change of polarity of potential at the rough surface, the flashover potential remained the same as the one obtained for the smooth surface of a sample. 17

The above phenomenon is explained by an increase of the adsorption of water and water vapor by the rough part of the external surface of a dielectric. As a result of this adsorption there is a lowering of surface resistance of a solid dielectric.

A lower surface resistance of solid dielectric prevents accumulation of surface charges. As a result we obtain a more uniform distribution of the electric field.

2.1.4. ROUGHNESS OF THE SURFACE OF CONTACT (JUNCTION) BETWEEN SOLID DIELECTRIC AND ELECTRODE

There are no data in the literature which would specifically describe the effect of roughness of the surface of contact between solid dielectrics and electrode.

Kofoid [84, 85] mentions briefly the presence of a gap between a solid dielectric and cathode surface. If both surfaces could be made ideally smooth, the contact of these surfaces would be also ideal, and then there would be no strengthening of intensity of the electric field in the gap, arising from

in-series layering of solid dielectric in vacuum.

In practice, there is no possibility of achieving such an ideal contact. Hence, there always exist gaps between the cathode and surface of a solid dielectric. Kofoid in his work [71, 72] assumed an idealized shape of such a gap and calculated intensity of the field in the gap. Calculations were based on the assumption that thickness of the gap is very small in comparison with the total thickness of a solid dielectric. He has not done, however, any measurement of the intensity of field in the gap, nor of the flashover voltage for various degrees of roughness at the contact between the solid dielectric and electrode.

In order to avoid the presence of a gap between a solid dielectric and electrode, some investigators [52, 54, 71, 96] resorted to metallization of surfaces of solid dielectric.

2.1.5. VOLUME RESISTIVITY OF SOLID DIELECTRIC

The effect of volume resistivity of solid dielectrics was investigated by Gleichauf [36, 37] for glass samples with different content of sodium. The content of sodium in glass determines its volume resistivity. After studying flashover potential for glass samples with different content of sodium, Gleichauf concluded that the volume resistivity of a solid dielectric has no effect on the voltage of flashover.

Gibson [35] also investigated the effect of volume resistivity of porcelain on flashover potential. He changed volume resistivity by changing the temperature. He found a decrease of flashover voltage with increase of the temperature of porcelain attributing this fact to a decrease in volume resistivity of porcelain. 118

It is difficult to draw any meaningful conclusion about the effect of volume resistivity on flashover potential along the surface of solid dielectrics, since not many results are available

and moreover, in the opinion of this author, in studies [35, 36, 37] along with changes of volume resistivity in the investigated samples there was also a change in surface resistance, which was not mentioned by the authors, and which has a profound effect upon the mechanism of flashover along a solid dielectric in vacuum.

2.1.6. SURFACE RESISTIVITY OF SOLID DIELECTRIC

The effect of surface resistivity of a solid dielectric upon the value of flashover voltage along a solid dielectric in vacuum was also investigated by Gleichauf [36, 37]. He used layers of silicon oil to cover external surfaces of glass 857 and of boron glass Pyrex 7740. Samples of glass 857 had a low flashover voltage as compared with glasses of other compositions. After covering samples of glass 857 with silicon oil, the value of their flashover potential increased by from 25 to 65%. Gleichauf concluded that an increase of the flashover potential was caused by an increase of surface resistivity resultant from the coverage of surfaces of solid dielectric with silicon oil.

This conclusion is in contradiction with results of studies by Srivastav [110], who found that coverage of a solid dielectric with semiconducting layer results in an increase of electric strength since a reduced surface resistivity prevents accumulation of charge on surfaces of a solid dielectric.

Fryszman [33] also found that the flashover voltage increased by a factor of about 2.6 when a part of external surfaces of solid dielectric near the cathode was covered with a semiconducting layer.

It is obvious from the above that there is disagreement between results obtained by various investigators, and there is lack of meaningful data on the relation between surface resistance and flashover potential.

2.1.7. COEFFICIENT OF SECONDARY EMISSION OF ELECTRONS FROM SURFACE OF SOLID DIELECTRIC

The effect of the coefficient of secondary emission of electrons from surfaces of solid dielectric was analyzed by several investigators, in connection with the phenomenon of charging of dielectric surface.

Gleichauf [36, 37] mentioned a possibility of the effect of secondary electron emission from dielectric surfaces on the surface strength, and suggested a possibility of changing the distribution of intensity of field caused by secondary emission, which may be dependent on the density of the dielectric. Thorough investigations of the mechanism of charging the surface of solid dielectric were carried out by Boersch and coauthors [12]. 119

A. Watson [126] postulates that the potential of flashover along the surface of a solid dielectric is dependent on the secondary emission, although his hypothesis on the appearance of primary electrons differs from the view of remaining authors. He suggests that primary electrons appear as a result of thermal emission from the surface of solid dielectrics.

R. Hayes and G.B. Walker [62] studied the effect of secondary emission on the flashover potential along the surface of samples of titanium oxide and of titanium oxide coated with glaze. They measured the coefficient of secondary emission and they obtained the same value for both types of investigated samples. The initial value of flashover voltage was 20 kV/cm for samples of titanium oxide, and 22 kV/cm for titanium oxide covered with glaze. But titanium oxide coated with glaze showed a noticeable increase of electric strength after conditioning, and the value of flashover potential was then similar to that of the sample of glass, which has the maximal coefficient of secondary emission $\delta_m = 2.3$. The value of δ_m for glazed titanium oxide measured in the work [62] was 1.2. Comparison of these

results indicates that there is no relation between the value of the coefficient of secondary emission δ_m and flashover potential along a solid dielectric.

In contrast to the above mentioned studies, A. Fryszman, T. Strzyz and M. Wasinski [33] suggest a possibility of increasing electric strength through the use of a solid dielectric with a low coefficient of secondary emission and a low surface resistivity.

J.D. Cross [22, 23] for a sample used aluminum oxide, a material of high density and a high coefficient of secondary emission $\delta_m = 6.4$ (Figure 2.8). For coating material he took copper oxide, which has a low coefficient of secondary emission $\delta_m = 1.25$, and chromium oxide, for which $\delta_m = 0.97$. Results of investigations (Figure 2.9) show a noticeable increase of the surge electric strength for samples covered with copper oxide and with chromium oxide. On the other hand, at direct (constant) and alternating potential a considerable increase in strength is observed when alundum samples are coated with chromium oxide.

The value of the coefficient of secondary emission depends very much on contamination of the surface of solid dielectrics, and particularly on the presence of such substances as a thin layer of oxide and a carbon deposit. Values of the coefficient of secondary emission are reported for pure surfaces and refer to the room temperature. During discharges along a solid dielectric in vacuum the condition of surface of solid dielectrics undergoes changes, hence in the course of consecutive flashovers the coefficient of secondary emission also changes.

This fact is confirmed by the publication of Chatterton and Davies [16] which reports changes of the coefficient of secondary emission before and after flashovers (Figure 2.10). The increase of surface strength as a function of the number of flashovers is explained as due to decreases of the coefficient

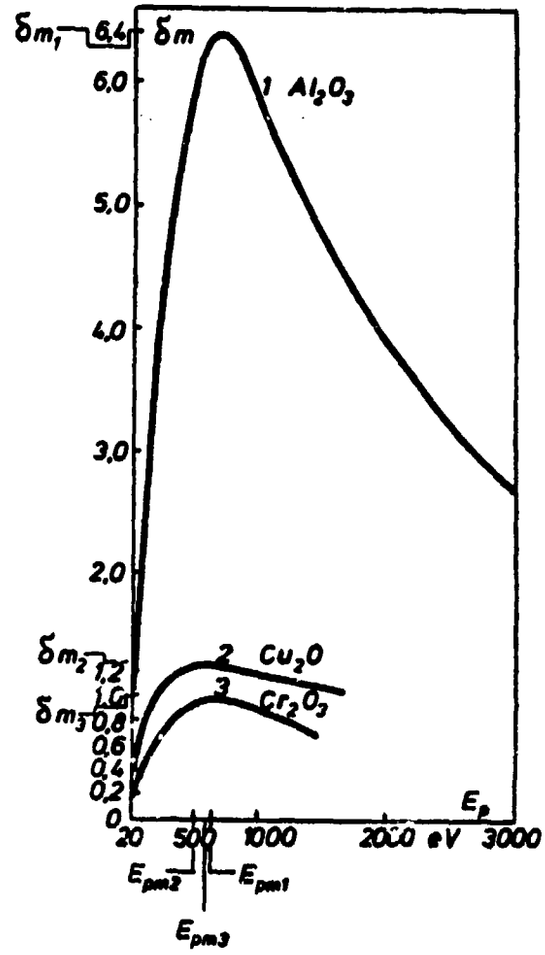

Figure 2.8. Coefficient of secondary emission δ as a function of the energy of primary electrons [114]: 1 - alundum (Al_2O_3), 2 - copper oxide (Cu_2O), 3 - chromium oxide (Cr_2O_3)

of secondary emission at consecutive flashovers.

The results of studies indicate that there is a dependence between the coefficient of secondary emission of electrons from dielectrics and the flashover potential along the surface of a solid dielectric.

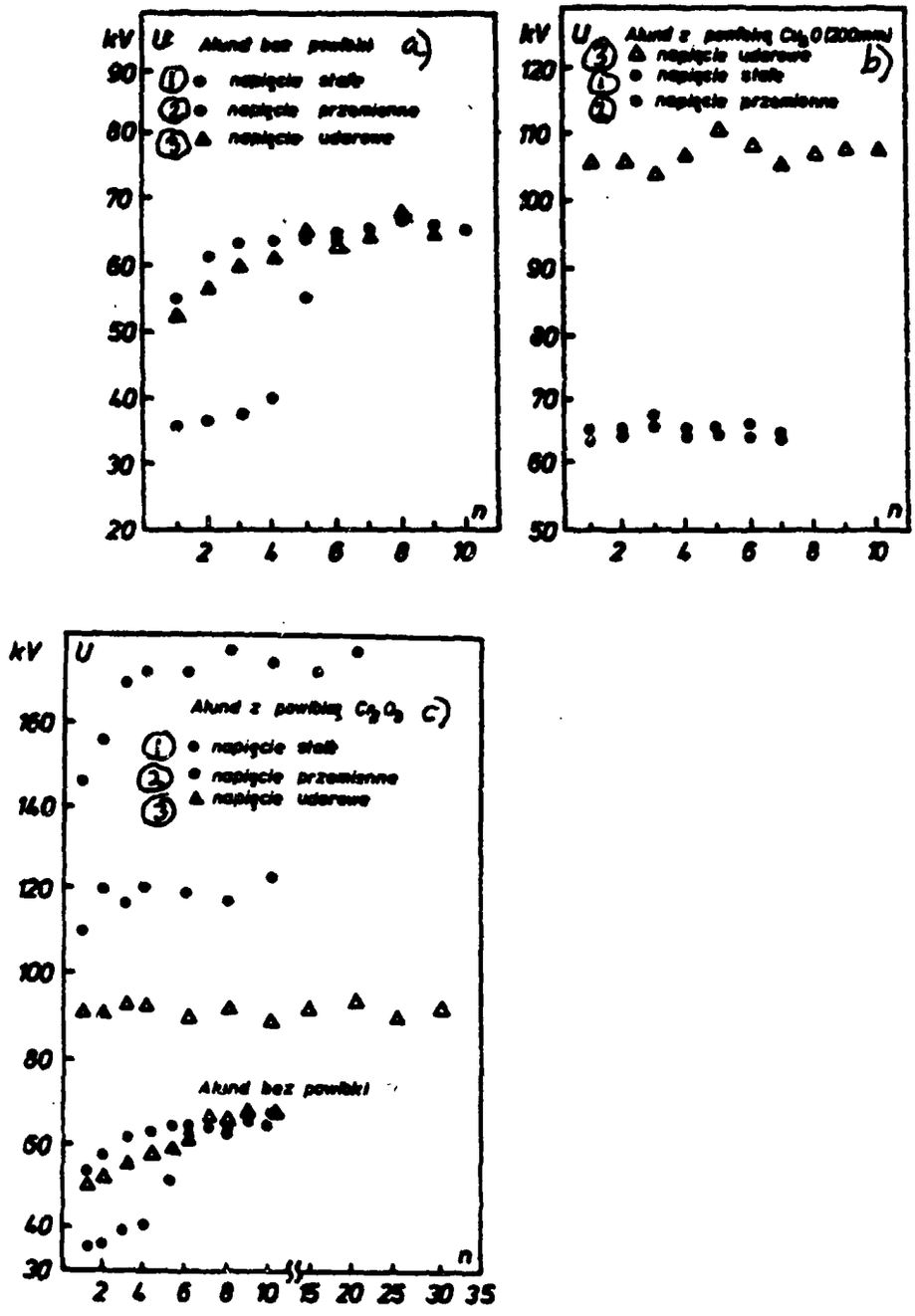

Fig. 2.9. Flashover potential as a function of the number of flashovers for alundum sample [22, 114]: a) alundum without coating, b) coated with copper oxide, c) coated with chromium oxide; 1- direct (constant) potential, 2 - alternating potential, 3 - surge potential.

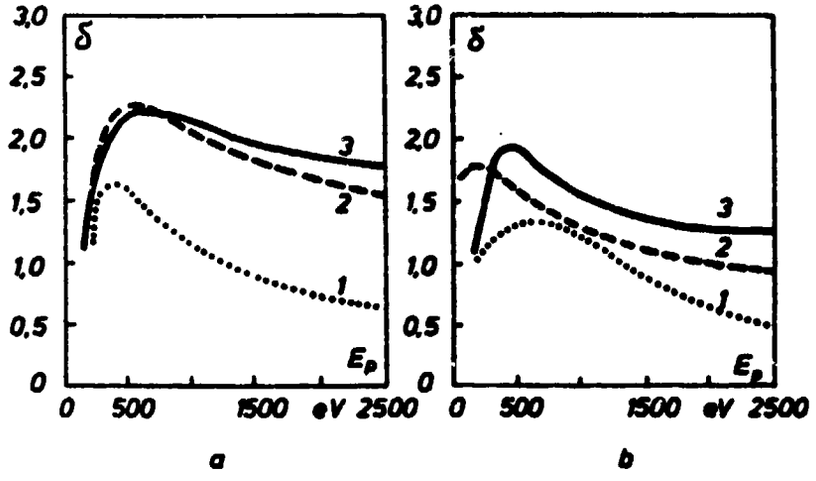

Figure 2.10. Coefficient of secondary emission δ as a function of the energy of primary electrons E_p [16]:
a) before flashovers, b) after flashovers;
1 - organic glass, 2 - alundum (Lucalox),
3 - glass (Macor)

A general conclusion that can be drawn from experimental results is that the higher is the potential of flashover along solid dielectric the lower is the coefficient of secondary emission δ_m from this dielectric.

2.1.8. WORK FUNCTION OF ELECTRON FROM SOLID DIELECTRIC

There are no data in the literature which would indicate any possibility of the effect of work function of the emission of electrons from surfaces of solid dielectric upon the potential of flashover along this surface.

As was mentioned before, Watson [127] suggests that the primary electrons appear as a result of thermal emission of electrons from the surface of solid dielectrics and not from the solid dielectric-cathode junction. Should this theory be right, which is however rather unlikely, then the thermal work function would play an important role in the mechanism of flashover along the surface of a solid dielectric.

2.1.9. DIELECTRIC PERMEABILITY OF SOLID DIELECTRIC

Relative dielectric permeability of solid dielectric changes the potential of electric fields in the gap between the dielectric and electrode, and causes changes of the pre-discharge current initiated by field emission. Many experiments were performed in order to determine the effect of relative dielectric permeability upon the potential of flashover. Gleichauf [36, 37] finds that dielectric permeability does not play any role in the mechanism of flashover. However, many investigators confirmed a considerable effect of dielectric permeability on the flashover potential. Kofoid [71, 72] reports that the potential of electric fields at the cathode-dielectric junction, deciding the emission of electrons from the cathode, is dependent on dielectric permeability of solid dielectrics. The potential necessary to liberate electrons increases with a decrease of relative dielectric permeability of solid dielectrics. 23

Akahane et al. [2, 3] and Ohki et al. [97] report that they measured a higher flashover voltage for solid dielectrics having a lower dielectric permeability (Figure 2.11).

Nagabhushana and Gopalakrishna [96] investigated the possibility of increasing the electric strength by the use of a thin foil of various materials placed between a porcelain sample ($\varepsilon_w = 7.0$) and the cathode. The obtained results indicate that the flashover potential increases when the dielectric permeability of thin foil decreases.

Suzuki [115] found that a ceramic material placed in vacuum has the higher value of the potential of surface flashover, the lower is its dielectric permeability.

It follows from the above data that the potential of surface flashover is higher in general when the dielectric permeability of investigated solid dielectrics is lower. 24

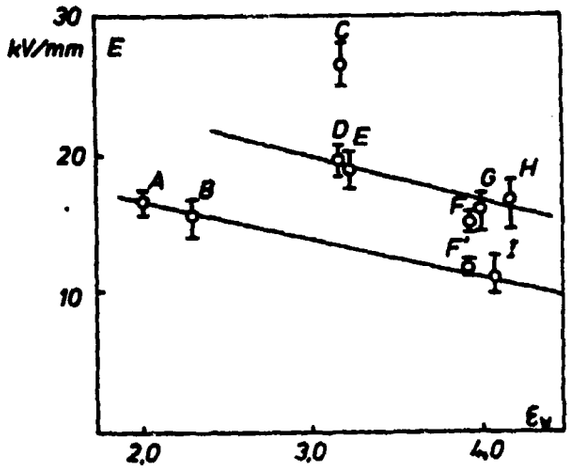

Figure 2.11. Intensity of electric field during flashover at the surge potential as a function of dielectric permeability of the sample [97] :

A - Teflon	(ε_w = 2.0)
B - Polyethylene	(ε_w = 2.3)
C - Polystyrene	(ε_w = 3.2)
D - ABS type resin	(ε_w = 3.2)
E - Polycarbonates	(ε_w = 3.2)
F - Conditioned glass	(ε_w = 4.0)
F'- Unconditioned glass	(ε_w = 4.0)
G - Epoxy resin A	(ε_w = 4.0)
H - Epoxy resin B	(ε_w = 4.2)
I - Polyamides	(ε_w = 4.1)

2.1.10. COEFFICIENT OF DIELECTRIC LOSSES

It is obvious that at alternating potentials, and particularly at high frequencies, the coefficient of dielectric losses may have large importance in the process of flashover along the surface of solid dielectrics in vacuum. Although many investigators report electric strengths for testing direct potential, alternating

potential of industrial frequency, and surge potential, there are not many works from which one could get some ideas about the effect of the coefficient of dielectric losses on surface strength of solid dielectric in vacuum.

Hayes and Walker [62] and Lewis [124] studied the flashover potential using high frequencies, but they do not report the effect of the coefficient of dielectric losses. It appears, however, that at a high frequency, a considerable amount of heat will evolve from a solid dielectric with large coefficient of dielectric losses and its temperature will be higher than that of a solid dielectric having a small coefficient of dielectric losses. The use of solid dielectrics with a high coefficient of dielectric losses may lead, in the final stage, to the destruction of solid dielectrics through the strong rise of its temperature, as a result of poor heat dissipation in vacuum.

2.1.11. THERMAL CONDUCTIVITY

We have not found any publication that would deal with the effect of thermal conductivity of solid dielectrics on the potential of flashover along solid dielectrics in vacuum.

Gleichauf [36, 37] made a short remark that thermal conductivity would have no significant effect on surface strength, if we assumed a fast progress of electric discharge. We can admit that the effect of thermal conductivity will be considerable in the case of covering the surface of solid dielectrics with a semiconducting layer, which is the cause of the evolution of heat at the application of direct or alternating potentials for a prolonged time.

2.1.12. DEGASSING ABILITY OF INVESTIGATED SAMPLE

One can distinguish two types of degassing ability of a solid dielectric placed in vacuum, namely : evaporation of insulating material caused by the reduction of pressure, and elimination of gases from the surface of solid dielectrics during electric discharge. The phenomenon of degassing of dielectrics in vacuum has a considerable effect on surface strength, and for this reason many investigators dealt with this problem. 25

Gleichauf [36, 37] studied the effect of pressure of vapors eliminated from solid dielectrics for boron glass (7740 Pyrex) and sulfur. These two dielectrics have similar physical properties, except that sulfur has a higher vapor pressure. The measured potential of flashover along these two solid dielectrics in vacuum was nearly the same. Hence, Gleichauf concluded that evaporation of solid dielectrics has no significant effect on the flashover voltage.

Srivastava and Tourreil [110] analyzed the composition of residue gases in the vacuum chamber using a spectrometer. Their results indicate presence of a large amount of water and vapors of oils coming from pumps, and of other gases such as N_2, O_2, CO etc. The gas analysis reported in the work [110] was done before the flashover. Srivastava and Tourreil [110] report also that the pressure increases before the appearance of flashover, and they analyzed also the composition of gas during this rise of pressure. The results showed that there is an increase of the amount of all the components of residual gas in the vacuum chamber, and particularly of hydrogen. It is thought, on the basis of these results, that the evolution of hydrogen may be connected with dissociation of water vapor adsorbed on the surface of dielectrics. For practical applications of organic material they suggest the use of Teflon, organic glass and high-pressure polyethylene, and they reject epoxy resins.

Kassirova and Tuzova [69] studied compositions of gas evolved

during discharges. The obtained spectrographic results indicate that a large part of liberated gas is the result of elimination of gases absorbed in surface layers, such as nitrogen, water vapor and hydrocarbon groups. A dependence between the material of the sample and composition of the gas evolved was also observed. There can occur decomposition of solid dielectrics as a result of electric discharge.

Akahane et al. [3] also used spectrographic techniques to analyze the composition of gas before and during the flashover along the surface of solid dielectrics for samples of polyethylene and boron glass.

The following conclusions were derived from studies [3]:

1) both the investigated dielectrics evolve gases before the flashover.
2) during the flashover, polyethylene evolves a large amount of hydrocarbons,
3) polyethylene evolves more gases than does boron glass,
4) for glass, the amount of evolved gases decreases with increase of the number of flashovers.

Ohki et al. [97] studied the surge potential of flashover using glass and thermoplastic materials, and two types of resins. They noticed the appearance of paths on the surface of all organic materials after discharges. The number of discharges (flashovers) necessary for the formation of such a path is different for each dielectric. The highest resistance to the formation of such paths was exhibited by samples of polyethylene and polyamide. Epoxy resins were in the second place, polystyrene - in the third, while polycarbonates and polytetrafluoroethylene were the most vulnerable to surface degradation. The results concerning Teflon obtained by Ohki [97] differ from those presented by Srivastava [111].

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Kuffel et al. [79, 53] also observed strong erosion of surfaces of organic dielectrics after conditioning by means of flashovers.

From this review of the results of investigations one can conclude that the phenomenon of degassing of dielectrics in vacuum and degassing during discharges has a considerable effect on the flashover potential and mechanism of flashover along solid dielectrics in vacuum.

2.2. EFFECT OF PARAMETERS OF ELECTRODES ON SURFACE STRENGTH IN VACUUM

2.2.1. SHAPE OF ELECTRODES

Since the shape of electrodes has a considerable effect on electric strength, a large number of investigators were concerned with this problem. The majority of them used the system of flat electrodes with edge profile of the pattern of Rogowski, which ensured a uniform or nearly uniform distribution of field. Some investigators used other systems, such as coaxial cylinders [42, 115, 116] and edge electrodes [115], and placed solid dielectrics of cylindrical shape between the electrodes. Other shapes of electrodes were also investigated [17, 71, 90, 93] attempting to reduce the intensity of electric fields at or near the solid dielectric-cathode junction, often by making a dent (cavity) in the electrode.

The author wishes to draw attention to the fact that, from a practical viewpoint, the concept of electrode systems is very important for the increase of strength of insulation systems. A change of the shape of electrodes affects the field distribution not only at or near the electrode-dielectric junction, but also along the surface of solid dielectrics. Hence, when analyzing the mechanism of flashover we have to take into account the shape of electrodes. For instance, if we have an electrode with cavity and a part of solid dielectric is located in this cavity, then

there will be a component of the field perpendicular to cylindrical surface of dielectric, even in the absence of surface charge.

2.2.2. ROUGHNESS OF ELECTRODE SURFACE

Discharge in vacuum gaps depends strongly on roughness of the surface of electrodes. However, surprisingly little information can be found about the effect of the roughness of electrodes in the case of flashover along solid dielectrics in vacuum. Roughness and microscopic protrusions are always present on the surface, even when electrodes appear to be smooth and polished. The field intensity is increased at sharp edges and may be sufficiently high to cause field emission at or near the solid dielectric-cathode junction. From this aspect, many authors assumed that a rough surface of electrodes is the reason for lowering of flashover potentials and in their studies they tried to eliminate the roughness of electrodes. However, Kalyatskii and Kassirov [67] found that there was no considerable difference in the surge potential of flashover along the samples of polymethylmethacrylate located between rough and polished electrodes. It was not reported how the surface was polished or made rough; hence it is difficult to make any comments and judgement on the cited observations. [27]

Mosciicka-Grzesiak [91, 93] reported results of measurements of flashover potential along a ceramic insulator 25 mm long as a function of the unevenness of electrode surfaces (Figure 2.12). The flashover potential becomes smaller with an increase of the height of protrusions R_z. The effect of electrode smoothness is different for particular materials.

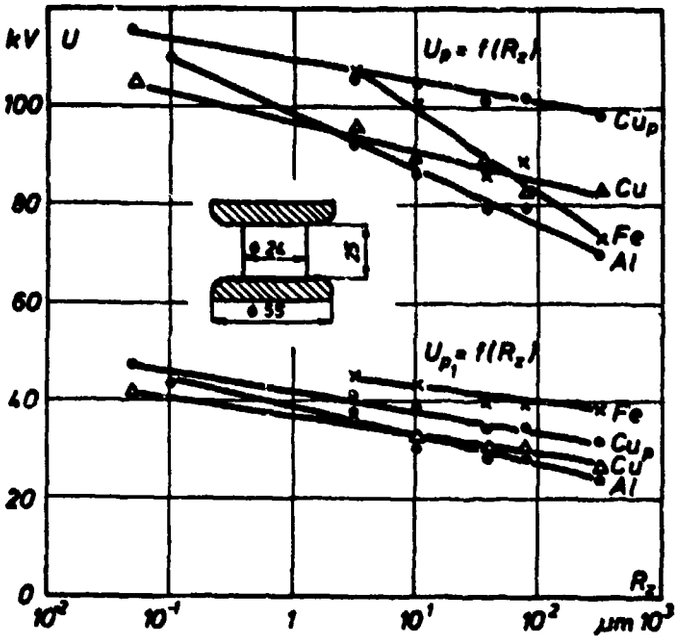

Figure 2.12. Flashover potential U_p and voltage of the first flashover as a function of the value of height of protrusions of surface R_z for steel, aluminum, usual copper and vacuum copper U_{p1} [93]

2.2.3. WORK FUNCTION OF ELECTRONS FROM ELECTRODE

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As was already mentioned, theoretical value of the current of field emission depends on the work function of electrons from the material of cathodes at a given temperature. However, experimental results indicate that the flashover potential for a vacuum gap is not directly dependent on the work function, although the effect of electrode material on flashover potential is evident.

In the case of flashover along solid dielectrics, experimental data published by Gleichauf [36, 37] and by Kalyatskii [67]

indicate that the work function of electrons from the material of electrodes has no significant effect on the flashover potential. The results of Moscicka-Grzesiak (Figure 2.12) also show that the work function of electrons from electrode has no significant effect on the potential of flashover, although there is an effect from the kind of electrode material.

The amount of information pertaining to the effect of the material of electrodes is very limited, and it is perhaps too early to conclude that the work function has no effect on the potential of flashover. It is possible that the effect is not visible in the presence of more dominant factors, which appear in connection with the presence of solid dielectrics between electrodes.

2.2.4. SECONDARY EMISSION FROM ELECTRODES

In addition to the primary emission of electrons from cathode, such as the field emission or thermal emission, there is also the possibility of the secondary emission of electrons as a result of the bombardment of cathodes with ions or of the action of photons.

When anodes are subjected to bombardment with electrons having a suitable energy, we may have emission of secondary positive ions and X-ray radiation.

The phenomena of secondary emission from electrodes may have a certain effect on the process of surface flashover.

2.2.5. MELTING TEMPERATURE OF THE MATERIAL OF ELECTRODE

Similarly as in previous Section 2.2.4, no dependence between the melting temperature of the material of electrodes and flashover potential was established experimentally. Erven et al. [27] suggest that metals with low melting temperature (copper, nickel, aluminum etc) suffer a more intense damage to anodes during a spark discharge.

Graneau [42] remarks that titanium is a good material for electrodes, since it has a high mechanical strength and a relatively high melting temperature.

2.3. EFFECT OF THE PARAMETERS OF EXPERIMENTAL CONDITIONS

2.3.1. PRESSURE AND COMPOSITION OF GAS

Several investigators studied the effect of pressure on the potential of flashover along solid dielectrics [28, 36, 37, 76, 100, 105, 122] and their results indicate that the pressure has no significant effect on the flashover voltage in the range from 133.322×10^{-4} Pa to 133.322×10^{-7} Pa (from 10^{-4} to 10^{-7} Tr).

Eastham [28] found no noticeable effect of the admixtures of other gases, e.g. Cl_2, SF_6, O_2, on flashover potential. The gases were introduced into the vacuum chamber, and the pressure rose from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} to 10^{-4} Tr).

Gleichauf [36, 37] reports that he found no effect of pressure, in the range from 5×10^{-6} Tr to 5×10^{-3} Tr, on flashover potential of investigated samples.

On the other hand, Ramm [100] shows that for a pass insulator 65 cm long placed in vacuum the flashover potential depends on pressure (Figure 2.13). Quantitative values of strength are also dependent on mounting of protective corners (edges), hence on distribution of electric field, although the curves $U = f(p)$ for insulators with corners and without corners have similar shape.

Smith [105] investigated surface strength for surge potential 30 μs for a sample of the shape of cones, and found no effect of pressure in the range from 10^{-4} Tr to 10^{-2} Tr; but at further rise of pressure the electric strength of samples decreased rectilinearly.

Tyman [122] studied surface strength as a function of pressure at alternating potential for a ceramic sample 5.7 mm

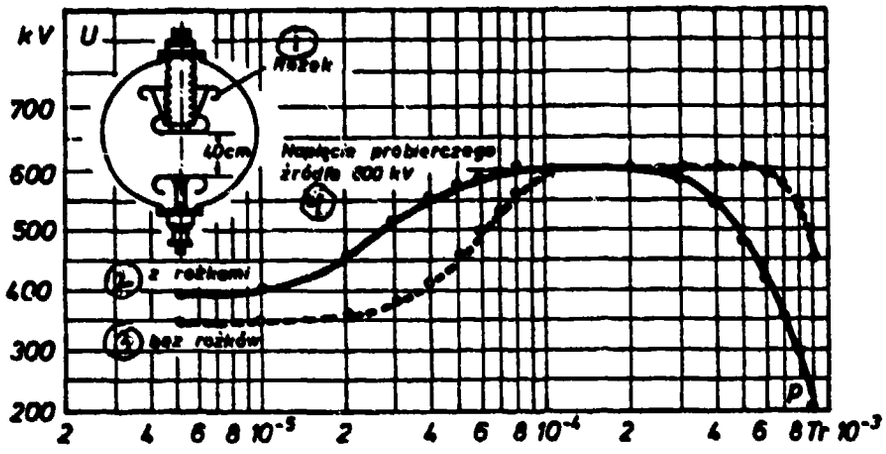

Figure 2.13. Flashover potential as a function of pressure for a pass insulator placed in vacuum [100]: 1 - corner (edge), 2 - with corners, 3 - without corners, 4 - test supply potential 600 kV

long, and did not observe any changes in electric strength in the range from 10^{-5} Tr to 10^{-3} Tr.

On the basis of results of our studies [76], the author considers that the pressure plays a considerable role. The results of investigations [76] will be discussed in Section 5.1. Similarly, the composition of gas must also play some role. This view is based on the observed phenomenon of un-conditioning. It is known that the value of flashover potential increases with the time of voltage conditioning. If samples are conditioned by means of a high potential and then the potential is removed for some time, the samples will partly lose the properties of conditioned samples, there will be un-conditioning. The phenomenon of unconditioning is not fully understood. It would be justified to assume that at least a part of the phenomenon of un-conditioning is connected with re-adsorption of gases by surfaces of electrodes and solid dielectrics. Moreover, the surface of solid dielectrics

adsorbs particularly strongly those gases which have a large dipole moment, e.g. water vapor, substances with low vapor pressure. These gases act as contaminants and they play important roles in the process of flashover. The degree of adsorption increases with increase of pressure, hence the pressure and gas composition may have an effect on the process of conditioning and un-conditioning.

2.3.2. TEMPERATURE OF THE DIELECTRIC-ELECTRODES SYSTEM

Several authors were concerned with the effect of temperature, both high and low, on surface strength of solid dielectrics in vacuum. By the terms "high" and "low" temperature we understand the temperature higher or lower than the normal temperature.

Srivastava [109] reported that the flashover potential did not suffer a noticeable change when the dielectric was heated by means of an infrared radiator.

Gibson [35] studied the phenomenon of ageing of porcelain samples subjected to the action of direct (constant) potentials at temperatures up to 200°C. He noted a lowering of the potential of flashover along the dielectric with the rise of temperature.

The effect of heating (up to temperature 800°C) on flashover potential along solid dielectrics was studied also by Kondratov [73] on samples from porcelain and steatite. The results of his studies (Figure 2.14) show that the surface strength first goes down, as the temperature increases, and then slowly increases as the temperature goes up. The minimum strength lies at about 120-150°C for both samples. Above the temperature 450°C the flashover potential was very low, and the samples often suffered damage.

Kuffel and Matsuyama [80, 81] reported results of the effect of temperature which are similar to the results of Kondratov. Measurements on samples of boron glass were carried out in the range from 20 to 150°C. The minimum in the flashover potentials occurred for the temperature from 80 to 100°C.

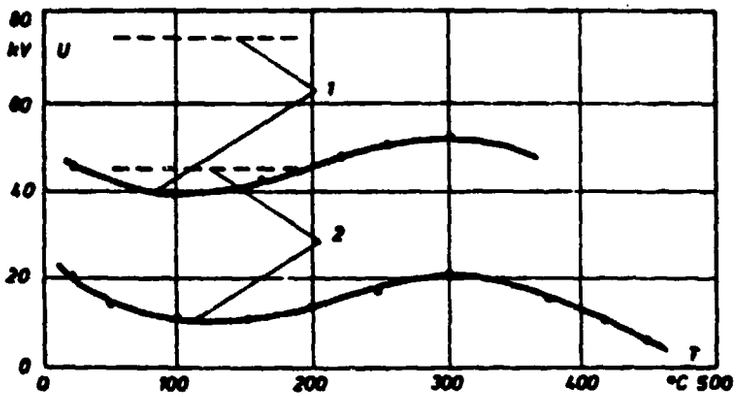

Figure 2.14. Flashover potential as a function of the temperature of solid dielectric and electrodes [73] : 1 - porcelain sample, 2 - steatite sample, ---- samples heated for a long time at the temperature 800°C before placing in the chamber

There are very few publications dealing with the effect of low temperature on flashover potential. From a practical viewpoint, institutions concerned with cryogenic cables and vacuum insulation have special interest in surface strength at the temperature of liquid nitrogen.

Graneau [42, 43] carried out investigations of flashover potential along solid dielectrics at the temperature of liquid nitrogen. Measurements were done on a system of coaxial electrodes made of aluminum.

It is difficult to evaluate the effect of temperature on surface strength on the basis of analyzed investigations, since they involved different electrode systems and different insulation materials.

2.3.3. CONDITIONING

The flashover voltage along solid dielectric in vacuum increases at first as a function of the number of discharges. Later it reaches a constant value at consecutive flashovers. This phenomenon has been called the conditioning.

The conditioning of samples is a very important factor, deciding the value of flashover potential, hence many investigators dealt with this problem [22, 26, 36, 42, 54, 76, 79, 97, 104] .

The effect of conditioning partially disappears when solid dielectric which is in vacuum is disconnected from the potential for some time. This phenomenon has been called the un-conditioning. The degree of un-conditioning depends on previous treatment of solid dielectric and electrodes. After un-conditioning, the flashover voltage after consecutive discharges usually increases relatively faster than in the previous conditioning of the new sample.

The rate of conditioning of samples is dependent on the kind of solid dielectric, as well as such factors as the kind and value of applied potential. Moreover, the time of conditioning is influenced by the height of applied pressure, the value of resistance put in series with investigated systems, etc. Glass and ceramic samples show a slower conditioning than samples from thermoplastic dielectrics.

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Conducting paths and canals appear on surfaces of solid dielectrics, particularly organic ones, during the flashover, and the surface of solid dielectric undergoes degradation. This phenomenon is very undesirable. Hence, it is adviseable that in the case of organic dielectrics the conditioning be performed without discharges, and rather by keeping samples under potential which is somewhat lower than the expected flashover potential, in order to save samples from degradation. The conditioning without discharges at a constant value of potential is called the conditioning by means of field emission [56, 94] .

2.3.4. TYPE OF APPLIED POTENTIAL

A large number of works concern the effect of the type of applied potential on the value of flashover potential for various solid dielectrics in vacuum. The majority of investigations were carried out for constant (direct) potential, but also other types of potential are represented.

The value of flashover potential for a given type of applied potential depends on the material of samples and method of conditioning. For various materials the flashover voltage is the greatest for constant or surge potential. Kofoid [72] reports (Table 2.1) that the flashover voltage for steatite samples is the highest at surge potential, but for zirconium porcelain - at constant potential. On the other hand, barium titanate has the flashover voltage the same at alternating potential 60 Hz and at surge potential.

Kondratov [73] reported flashover voltage as a function of the length of solid dielectric for three types of potential (Figure 2.15). The flashover voltage of investigated samples is the highest at the impulse (surge) potential. The surface strength at the constant and alternating potentials is similar. For samples of small length (4 mm) the strength at constant potential is somewhat higher than at alternating potential. At impulse potential, the highest and the lowest values of flashover voltage are given. 33

Cross [22] and Sudarshan [114] studied the flashover voltage (Figures 2.8 and 2.9) of alundum (Al_2O_3) samples covered with copper oxide (Cu_2O) and chromium oxide (Cr_2O_3) using constant, alternating and lightning surge potentials. For alundum samples not covered with oxides the flashover voltage after conditioning was nearly the same. After covering of alundum sample with copper oxide (Figure 2.9b) the flashover voltage at surge potential increased about twice. The coating of sample with chromium oxide (Figure 2.9c) caused nearly threefold rise of strength at constant

Table 2.1

Flashover voltage for ceramic samples [72]

Material	Flashover voltage, kV		
	Direct (constant) potential	Alternating potential 60 Hz	Surge potential 1.5/40 μs
Steatite	> 40	44	50
Zirconium porcelain	> 40	36	40
Rutile	20	18	13
Barium titanate	6.5	7.5	7.5
Length of sample 1.17 cm, pressure 10^{-4} Tr			

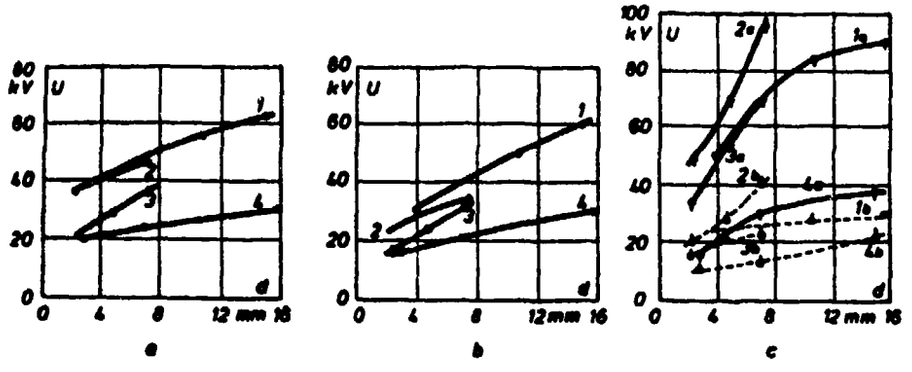

Figure 2.15. Flashover voltage as a function of the length of sample at the temperature 20°C [73] : a) constant potential, b) alternating potential 50 Hz, c) impulse potential 0.1/180 μs; ____ maximal values, --- minimum values; 1 - glass, 2 - steatite, 3 - alundum ceramic, 4 - glazed porcelain

potential, while the flashover voltage at impulse potential was the lowest.

For impulse potentials the value of flashover voltage usually goes down as the time of duration of the impulse wave front increases. Kalyatskii and Kassirov [67] found that the change of strength as a function of the time of duration of impulse wave front (Figure 2.16) depends on the kind of material and the length of samples.

The above remarks indicate that it is very difficult to make unequivocal conclusion about the effect of the type of potential on flashover voltage. The effect depends on many factors [54] mainly the type of dielectric, method of conditioning, length of samples, temperature.

2.3.5. IRRADIATION

Using quartz glass and boron glass Gleichauf [36, 37] found the lack of changes in surface strength for direct (constant) potential when the samples were subjected to the action of ultraviolet rays. He showed that the flashover potential remains constant, unchanged for the investigated solid dielectrics.

Kondratov et al. [74] obtained reduction of flashover voltage (Figure 2.17) for impulse potential a few μs long, after irradiation of samples before the application of test potential. The authors [74] explain this phenomenon as the effect of charge on surface of dielectrics, which is formed during irradiation.

The charge accumulated on the surface of solid dielectrics causes an increase in the conductance of samples. For impulse potential whose duration is larger than 10^{-5} sec, the charge on surfaces of solid dielectrics created as a result of secondary emission (caused by test potential) is considerably higher than the charge generated by ultraviolet radiation. This is the reason why Gleichauf [36, 37] did not observe the effect of irradiation on surface strength for constant potential.

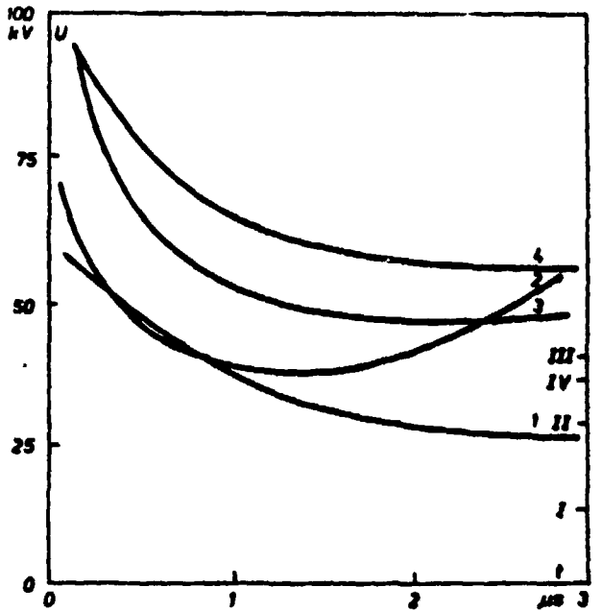

Figure 2.16. Voltage of flashover along solid dielectrics 9.5 mm long in vacuum as a function of the time of duration of the impulse wave front [67] : 1 - Teflon, 2 - organic glass, 3 - polyvinyl chloride, 4 - epoxy resin; I, II, III, IV - values of flashover voltage at direct (constant) potential

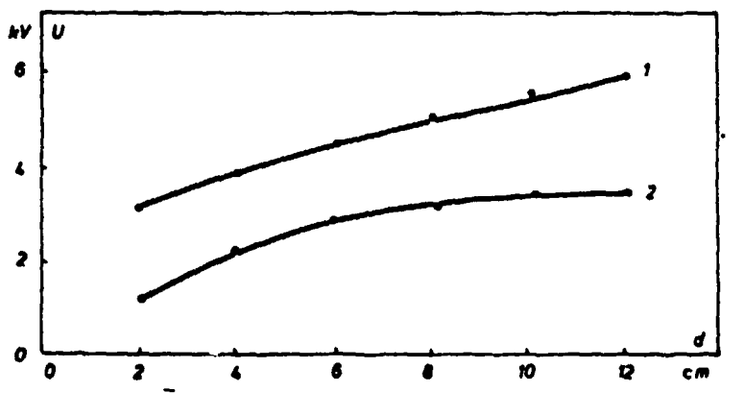

Figure 2.17. Flashover voltage for impulse potential as a function of the length of mica sample [74] : 1 - sample without irradiation, 2 - irradiated sample

2.3.6. IN-SERIES RESISTANCE IN THE TEST CIRCUIT

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The discharge current and discharge energy depend on the parameters of circuit of high potential, such as the source power, resistance connected in series with investigated object, capacity of the system, resistance of connecting elements, including grounding. If the energy of discharge is large, craters may appear on the surface of electrodes. At the same time, however, discharge current may smooth out the surface of electrodes by melting sharp protrusions, which causes an increase in flashover voltage for the vacuum gap.

The phenomenon of self-cleaning of electrodes as a result of discharge current is the same as in the system of electrodes without solid dielectric. The effect of resistance connected in series with investigated objects is very large, particularly on the process of conditioning. However, the number of publications dealing with the effect of resistance on conditioning is small [56].

Gleichauf [36, 37] found that the character of discharging is irreproducible when a resistor limiting the current to values below 1 A was connected in series with the investigated system.

The basic difficulty when applying resistors connected in series lies in determination of the value of flashover tential. For a criterion of flashover the majority of investigators accept the appearance of a bright spark, or a sharp drop of potential at the source.

Finke [30] and Graneau [42] report in their works that i · have not found any larger damage to the surface of solid dielectric and electrodes at high discharge currents. This is explained by the fact of increase of the value of resistance connected in series, as a result of the skin effect, since discharge in vacuum is a very fast process.

Nevertheless, a degradation of the surface of all solid dielectrics does take place during the surface discharge. The

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extent of the degradation of surfaces depends on the kind of material, type of potential, and primarily on the power of source and value of resistance connected in the circuit.

2.3.7. DIELECTRIC COATING ON ELECTRODES

Several authors [92, 93, 96, 119] investigated the possibility of increasing the electric strength of systems with solid dielectric by coating the electrodes with solid dielectric, and they gained a considerable increase of strength of such a system (Figure 2.18). However, after the flashover the coating of such a system has microcrevices which may reduce the electric strength of the system.

In view of some authors [55, 64, 98] the effect of insulating coatings on electrodes is of particular significance for increase of electric strength of the system only in the case of the first few discharges, since the next flashovers will involve already the coatings with microcrevices. The increase of electric strength depends on thickness of dielectrics, its tightness, dielectric permeability, and primarily the power of source and resistances connected in series with investigated systems.

2.4. DIRECTIONS OF STUDIES BY AUTHOR

As follows from the presented analysis of published work, the results of studies of the surface strength of solid dielectrics in vacuum are often contradictory, and the published data are not sufficient to attempt a synthetic presentation of the problem of electric strength of this system. One can find also the nearly total lack of studies concerned with surface strength of solid dielectrics in vacuum at switching potentials. This unsatisfactory state of knowledge in this area was a reason for undertaking the present work by the author. Studies of surface strength were

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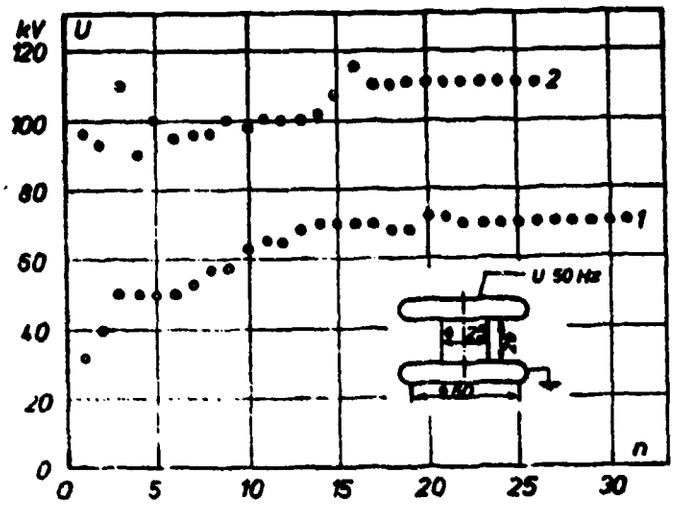

Figure 2.18. Values of flashover voltage corresponding to the consecutive discharges: 1 - noncoated electrodes, 2 - electrodes coated with Araldit lacquer, 40 μm.

limited to thermoplastic dielectrics because it is anticipated that just they will find broad application in cryogenic systems [42, 43].

On the basis of literature surveys, the following theses concerning the investigated system were postulated:

1. Surface strength of insulation materials in vacuum at switching potentials depends on the time of duration of the front wave of switching surge.
   a. With the increase of this time the flashover voltage should decrease, which is caused by accumulation of a larger charge on the surface of solid dielectrics.
   b. For long times of duration of the wave front of switching surge, a part of the charge should disappear from the surface of solid dielectric through surface conductance, resulting in an increase in flashover potential.

c. Considering the factors listed in Points 1a and 1b, the flashover potential along solid dielectrics in vacuum should have, similarly to the case of insulators in air, a minimum in the function of the time of duration of surge switching wave front.

2. Insulation materials in vacuum suffer degradation dependent on the number of flashovers. Energetic actions connected with the progress of discharges along the surface of solid dielectric lead to degradation of thermoplastic materials in vacuum as a function of the number of discharges, and to the appearance of canals conducting during the flashover.
   a. If consecutive discharges damage strongly the surface of thermoplastic materials then the surface strength will be affected by way of conditioning: type of potential, value of potential, number of discharges.
   b. Deterioration of insulating properties of thermoplastic dielectrics will be different for particular dielectrics.

The following program was outlined to confirm the postulated theses:

1. Preliminary investigations:
   a. Determination of the effect of pressure on surface strength.
   b. Determination of the effect of metallization of solid dielectric-electrode contact on surface strength.
   c. Study of the effect of conditioning parameters on surface strength: type of conditioning potential, number of flashovers, time of intervals between flashovers.
2. Proper studies:
   a. Study of surface strength as a function of the length of solid dielectric for three materials.
   b. Study of surface strength for direct (constant), alternating and lightning surge potentials.
   c. Study of surface strength for switching surges with

different times of duration of the surge wave front.

d. Study of the degree of degradation of samples as a function of the number of flashovers.

3. MECHANISM OF THE DEVELOPMENT OF FLASHOVER ALONG THE SURFACE OF A SOLID DIELECTRIC IN VACUUM

In spite of a large number of investigations carried out in the past there is still lack at present of one concordant view on the mechanism of flashover along solid dielectrics in vacuum. For a better picture of the above problem we shall outline several hypotheses proposed by various investigators.

All the hypotheses concerning the mechanism of the development of flashover in vacuum have one feature in common - the use of electrodes as a source of charges which condition flashover in vacuum. If between electrodes in vacuum there is a solid dielectric, then an additional source of charges may be provided by layers of gas adsorbed by surface, as well as the volume of solid dielectric.

The first description of causes which condition the surface flashover in vacuum was given by Gleichauf [36, 37] . He found that on increasing the potential between electrodes and solid dielectric there will appear a pre-discharge current. This pre-discharge current was in the range of 10^{-11} to 10^{-7} A, and single short impulses, called microdischarges, were up to 10^{-3} A. A further increase of potential between electrodes leads to discharge (flashover). During this increasing of potential there occur single surface discharges, characterized by faint flashes on the surface of solid dielectric. Gleichauf studied the effect of pressure and roughness of electrodes, and of roughness of solid dielectric on the value of flashover potential. He found a large effect of the method of conditioning the sample, i.e. time and value of applied potential, on the value of flashover voltage.

However, apart from determination of quantitative relationships regarding flashover potential, Gleichauf did not attempt to explain the mechanism of flashover along the surface of solid dielectrics in vacuum.

One of the oldest theories of the mechanism of surface flashover in vacuum belongs to Kofoid [71, 72]. He postulated that the flashover begins from the emission of negatively charged particles, mainly electrons, as a result of the increase of field in the gap between cathode and solid dielectric. Electrons emitted from the site of solid dielectric-cathode junctions collide with the surface of solid dielectric and surface of anode. They liberate from the anode positive ions and X-ray and ultraviolet radiation, which in turn hit the surface of cathode and solid dielectric, causing further emission of electrons. Kofoid found that there is emission of electrons at the site of solid dielectric-cathode junction, and his theory about liberation of X-rays and ultraviolet rays from anode was confirmed experimentally by Gleichauf [36, 37]. However, his hypothesis does not explain the phenomenon of accumulation of positive charge on the surface of solid dielectric.

Fryszman et al. [33] proposed theory similar at least with respect to the initial state of discharging, that is the emission of electrons from the site of the solid dielectric-cathode junction. Next, electrons colliding with the anode or with the surface of solid dielectric in the vicinity of anode cause the appearance of a positive charge from the side of anodes. The theory of Fryszman, Strzyz and Wasinski assumes that the surface of solid dielectric (Figure 3.1) in the vicinity of anode becomes gradually charged positively and reaches the potential of anode. It means that the surface of solid dielectric charged positively functions as a part of anode and increases the field density along the surface of solid dielectric. As a result, electrons are emitted with greater ease from the site of junction of solid dielectric with cathode.

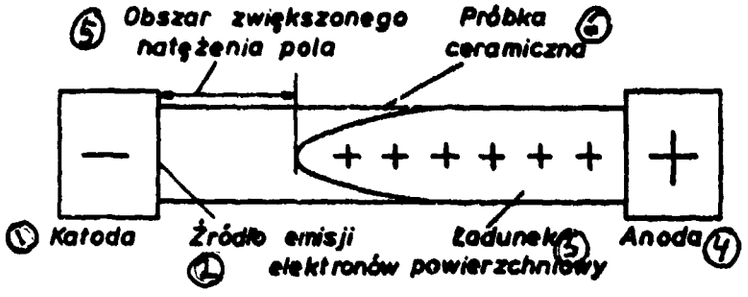

Figure 3.1. Distribution of charges on the surface of solid dielectric, according to the theory of Fryszman, Strzyz and Wasinski [33] : 1 - cathode, 2 - source of the emission of electrons, 3 - surface charge, 4 - anode, 5 - area of increased field density, 6 - ceramic sample

The charged surface gradually spreads in the direction of the cathode until the field density becomes sufficiently high to initiate the flashover along the surface of solid dielectric. When the electric arc forms, the positive charge disappears and the field intensity decreases to such an extent that the arc becomes extinguished. If a solid dielectric is exposed to many flashovers, its surface will become covered with a thin layer of metal evaporated from electrodes, which prevents accumulation of charge and in this way the flashover potential gradually increases. However, this theory does not agree with results obtained by Gleichauf, who found that the flashover potential along solid dielectric increases with the increase of surface resistance of solid dielectric.

Watson [127] studied the mechanism of flashover using short-lasting impulses and found that the rate of development of flashover is very high, and time to flashover is of the order of 10 μs. He suggests the appearance of thermal emission, which liberates electrons from solid dielectric. This causes positive

charging of the surface of solid dielectric. Positively-charged surface of solid dielectric attracts electrons, hence there is an increasing number of electrons hitting the dielectric. As a result of secondary emission there is the growth of positive charge on surfaces of solid dielectric leading to flashovers. The theory advanced by Watson differs from other theories about the inintial emission of electrons. The hypothesis by Watson does not explain the nonlinear character of flashover potential as a function of the length of solid dielectrics.

Bugaev et al. [14, 15] report that flashover voltage at constant potential depends on the pressure of residual gas. They assume that there is always a thin layer of gas adsorbed on the surface of solid dielectric. They carried out investigations of pre-discharge potential-current characteristics shortly before the flashover, and they studied the rate of the development of arc and its geometrical shape. On the basis of obtained results and assumption of the presence of gas adsorbed on the surface of solid dielectric they calculated pre-discharge current and obtained the value 1 A, the result in agreement with the value obtained experimentally. Hence Bugaev, Iskoldskii and Miesiac established that the discharge starts in the layer of adsorbed gas, and the flashover voltage depends upon the ability to adsorb gas by insulating material.

The first works which stated a dependence of flashover voltage on the phenomenon of secondary emission of electrons from the surface of solid dielectric were publications of Boersch et al. [12, 58]. In the last decade, Cross, Srivastava, De Tourreil and Sudarshan [20, 23, 110, 111, 114] developed a theory of the mechanism of charging the surface of solid dielectric through the secondary emission of electrons.

According to Boersch, Hamisch and Ehrlich [12, 58], primary electrons, which are in the system as a result of field emission, collide with the surface of solid dielectrics, causing

secondary emission of electrons from surfaces of solid dielectric. As a result of this secondary emission, a charge is formed on the surface of solid dielectric, dependent upon the coefficient of the secondary emission of electrons δ (Figure 3.2.).

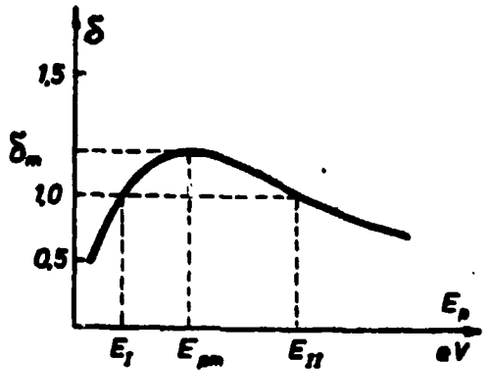

Figure 3.2. Coefficient of secondary emission of electrons δ as a function of the energy of primary electrons

The coefficient of secondary emission of electrons is a function of the energy of primary electron. To the coefficient of secondary emission $\delta = 1$ correspond two values of the energy of primary electron, denoted by E_I and E_{II} (Figure 3.2.). The surface of solid dielectric, which is under electric potential (constant supply of electrons), will be charged positively or negatively depending on the energy of primary electrons. For $E_I < E_p < E_{II}$ the coefficient of secondary emission of electrons $\delta > 1$, and the surface of solid dielectric is charged positively. If the energy of primary electron E_p is smaller from E_I or larger than E_{II} the coefficient of secondary emission of electrons $\delta < 1$, and the surface of solid dielectric is charged negatively.

The works [12, 58] show change of the charge density

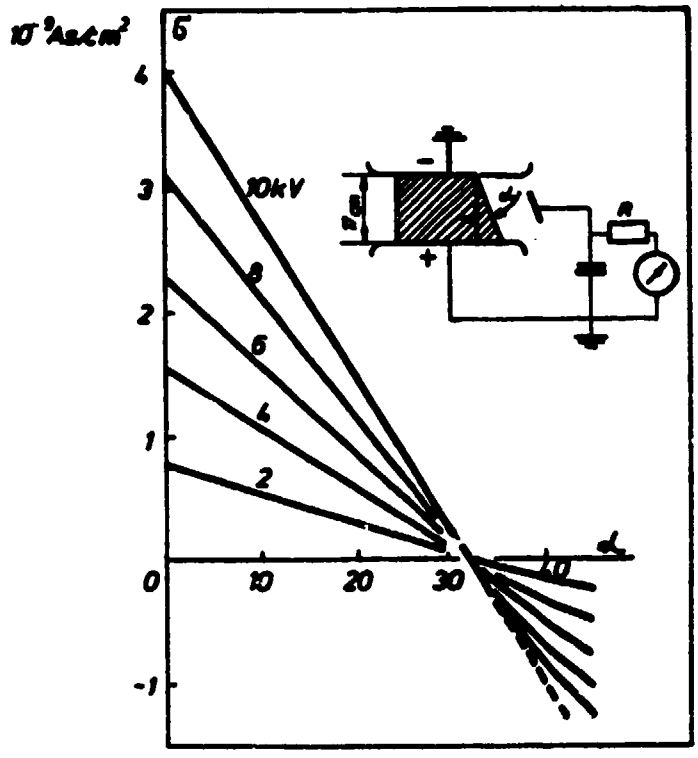

Figure 3.3. Change of the charge density on surface of solid dielectric as a function of the angle of inclination of solid dielectric α, for various values of test potential [12, 58]

on surface of solid dielectrics (Figure 3.3) as a function of the values of applied potential and the angle of inclination of the surface of solid dielectric to electrode.

In the mechanism given by Boersch, Hamisch and Ehrlich, the surface of solid dielectric is first charged positively (if $\delta > 1$) at the cathode, and then the positive charge moves in the direction of anode. It is assumed that routes of electrons causing the secondary emission are the same.

Cross and Srivastava, using an electron beam, also performed measurements of charge density on the surface of solid dielectrics formed at various potentials of electric field. The obtained experimentsl charge density was similar to the calculated density. According to Cross, the charge density on surface of solid dielectrics is different at particular points of insulator. Sections of solid dielectric may be charged positively or negatively, since this depends on the type of solid dielectric and on the energy of electron hitting the surface of solid dielectrics. 43

The authors of the work [114] carried out studies of the effect of the coefficient of secondary emission of electrons on flashover voltage (Figure 2.9) and distribution of charge on surface of solid dielectrics for three materials having different coefficients of secondary emission of electrons. They found that the charge distribution is dependent on values of applied potential, coefficient of secondary emission, and the angle of inclination of the surface of sample to electrode. For the time of duration of potential of the order of a few μs, the charge has no time to get established, hence we have an increase of flashover voltage for surge potentials.

The basic difference between the theory of Fryszman [33] and theories of Boersch [12, 58] or Cross [20, 23, 110, 111, 114] is the placement of positive charge on surface of solid dielectrics and the direction of its spreading. Fryszman postulated that the positively-charged part of surface of solid dielectric is first formed in the vicinity of the anode and then spreads in the direction of cathode. Theories of Boersch and Cross make opposite assumption that the surface of solid dielectrics near the cathode is charged positively, and then the charged surface extends towards the anode. The process described according to the model of Fryszman requires a longer time to reach the flashover than the processes according to Boersch or Cross.

Examining gases which were evolved shortly before the flashover, Akahane et al. [2, 3] found that they originated from solid dielectrics. They postulate that electrons emitted at the site of solid dielectric-cathode surface junction liberate gas adsorbed by the surface of these materials. A local increase of the pressure of gas at the surface of solid dielectric is the reason of flashover caused by charge accumulated on the surface of solid dielectric.

According to the theory of Akahane, the flashover voltage decreases with the amount of gas adsorbed by solid dielectrics, and with the amount of electrons emitted at the site of junction. In order to check this hypothesis, Akahane measured the flashover potential for polyethylene samples which had been heated for various periods of time, and found that the value of flashover potential goes down if the time of heating increases to 100 hours, and then reaches a constant value (Figure 3.4). He postulates also that the lowering of flashover potential depends on the oxidation connected with heating. This theory is similar to the theory proposed by Bugaev, and it contains the same problem of the presence of gas on surfaces of solid dielectric. 144

Avdienko and Malev [7, 8, 9] advanced a mechanism of surface flashover suggesting the gas model of flashover. They think that, as a result of desorption of gas from surfaces of solid dielectric, there will be formed a layer (cloud) of gas at the surface of the solid dielectric. Under the effect of applied electric fields the emitted electrons will cause ionization of gas particles in this gas layer, causing an increase in the number of electrons and consequently leading to appearance of a plasma channel which joins the two electrodes. The potential of surface flashover was calculated as a function of the amount of evolved gas. The effectiveness of desorption of outer layers of gas , according to these authors, should be higher than that from inner layers. It follows from this that, at the same field potential, the amount of desorbed gas as a function of time decreases, and

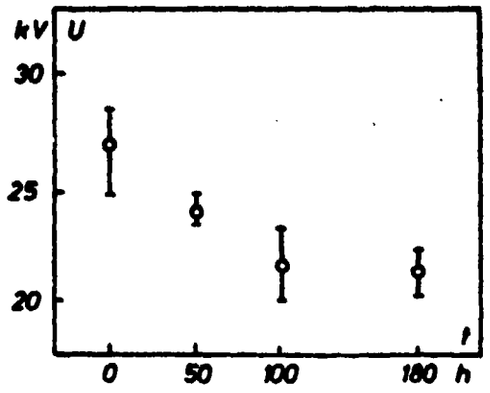

Figure 3.4. Flashover voltage as a function of the time of heating of polyethylene samples at the temperature 100°C [3], sample length 2 mm

surface strength increases. Such a process takes place during conditioning of samples. The proposed mechanism explains the reason for shortening of the conditioning time after thermal degassing of samples, and an increase of potential of the first flashover after a prolonged pressure conditioning.

Anderson and Brainard [4, 5] suggest a mechanism of the development of surface flashover in vacuum as a result of the secondary emission of electrons and desorption of gas from surface of solid dielectrics. This mechanism is based on the phenomenon of electron-stimulated desorption. In the given mechanism of flashover in vacuum it is assumed that after the application of potential there occurs charging of the surface of solid dielectric with positive charge, and the accompanying cascade of electrons, as a result of the secondary emission of electrons, has a constant value through a large part of time before the flashover. Bombardment of the surface of solid dielectrics with electron cascade causes the desorption of gas, which is partly ionized since it is mixed with a large number of electrons in cascade.

The electric field at the cathode edge of solid dielectrics becomes strengthened as positive ions accumulate, which in turn increases the degree of gas desorption and ionization. Processes of increase of the number of electrons lead to flashover. The proposed model of discharging allows to foresee the time to flashover and the dependence of flashover voltage on the length of solid dielectrics.

Bugaev et al. in works [14, 15], and Akahane et al. [2, 3] pointed to the importance of desorbed gas, and gave mechanism of the development of electron cascade; in the mechanism the authors assume that the discharge develops itself within the thin layer of gas adsorbed on surface of solid dielectrics.

Avdienko and Malev [7, 8, 9] suggest the mechanism of surface flashover, in which the discharging takes place in the layer of desorbed gas. They do not take into consideration, however, the secondary emission of electrons at the surface of solid dielectric.

Anderson and Brainard [4, 5] explain the mechanism of the development of surface flashover in vacuum as a result of the secondary emission of electrons and desorption of gas from the surface of solid dielectric.

4. APPARATUS, EXPERIMENTAL PROCEDURE AND TREATMENT OF RESULTS

4.1. APPARATUS

Investigations were carried out in a vacuum chamber where vacuum was obtained by means of a system of pumps, enabling to reach the vacuum of about 133.22×10^{-7} Pa (10^{-7} Tr). The system of vacuum pumps consisted of a rotational pump with the rate of pumping 190 l/min and an oil diffusion pump. General view of the test stand together with measuring instruments is shown in Figure 4.1.

Vacuum measurements were made by means of an ionization vacuum gauge with Penning type sensor placed in the base of vacuum chamber. Since it was found that the value of flashover voltage in the range of pressure from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} to 10^{-4} Tr) remained nearly independent of pressure, the measurements of flashover voltage were done at the pressure 133.322×10^{-5} Pa (10^{-5} Tr).

Diagram of the vacuum chamber is shown in Figure 4.2. The chamber consists of a glass cylinder of height 40 cm and diameter 30 cm, closed at both ends by means of stainless steel plates. The chamber was made hermetical by means of neoprene gaskets lubricated with special silicone grease.

Flat electrodes were made of brass covered with nickel. The diameter of electrodes was 15 cm, and the edges had curvature according to the formula of Rogowski, ensuring the uniformity of fields at sample length up to 30 mm.

As a solid dielectric placed between the electrodes for investigations we used: polymethylmethacrylate (organic glass), polytetrafluoroethylene (Teflon) and polyethylene. These materials have a large potential for application in cryogenic cables [42, 43] since they possess a high electric

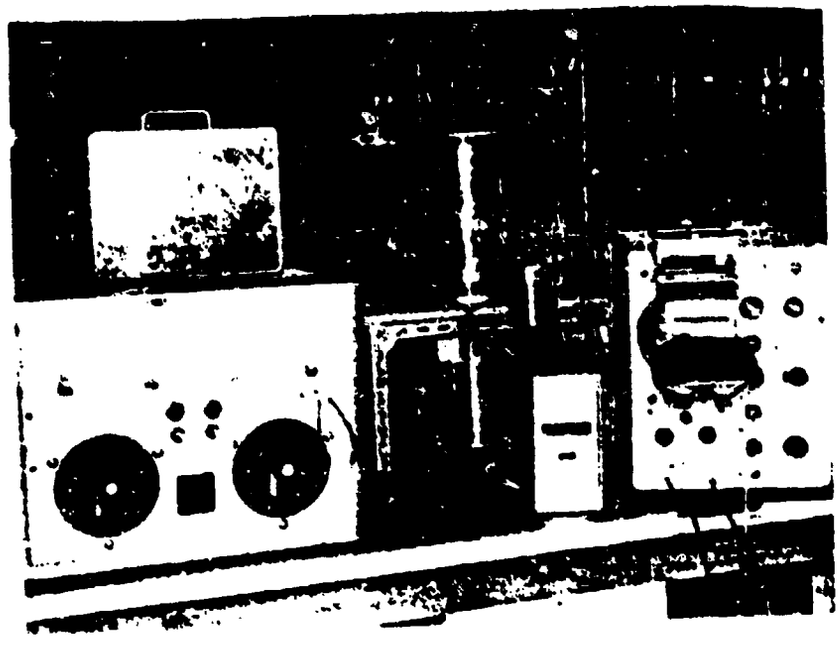

Figure 4.1. Test stand together with measuring instruments: vacuum chamber, a system of vacuum pumps, vacuum gauge, oscilloscope of company Tektronix type 585 A, voltage regulator, voltmeter

strength and it is relatively easy to obtain any planned shape of the insulator. Electrical properties of investigated materials are presented in Table 4.1. The samples had cylindrical shape of diameter 25 mm and of length 5, 10, 15 and 20 mm.

To ensure good contact between investigated samples and the electrodes, the ends of cylindrical samples were polished and then covered with a layer of silver by the method of vacuum evaporation. Moreover, a good contact between electrodes and silvered surface of solid dielectrics was obtained by means of pressure on the upper electrode equal to 196.133 kPa (2 kG/cm^2). Before placing in vacuum chamber the samples and

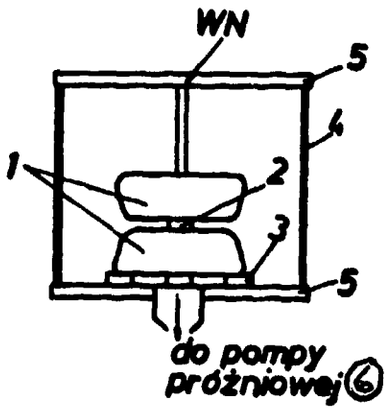

Figure 4.2. Vacuum chamber with a system of flat electrodes and solid dielectric between electrodes: 1 - electrodes, 2 - investigated sample of solid dielectric, 3 - insulators supporting the lower electrode, 4 - glass cylinder, 5 - metal plates, 6 - to vacuum pump, WN - high voltage

electrode . e washed with trichloroethylene and then dried and wiped with linen (lint free) material.

As a source of high voltage of alternating type we used a test transformer 300 kV, 50 kVA; a system of rectifiers was connected to obtain direct potential. In order to reduce the shorting current during the flashover, we applied a resistor of value 2 M.Ω . The state of shorting of the system was interrupted after 9 ms.

One of the main aims of investigations was to check the effect of the shape of wave simulating the switching overvoltage on the flashover potential. As a source of switching voltages we used a generator of switching surges with time of duration of the surge wave front from 1.2 μs to 600 μs and the time to half-peak from 50 μs to 3000 μs. The switching surge of required shape was obtained from a two-step generator (Figure 4.3) by changing the resistances R_1, R_2 and capacity C_1 in the circuit. Capacities C_2 and C_3 formed a capacity divider, which supplied the oscilloscope of company Tektronix type 585 A, with long glow

Table 4.1
Electrical properties of investigated insulating materials

No.	Property	Polymethyl methacrylate (organic glass, Plexiglass)	Polytetra fluoroethy lene (Teflon)	Poly ethy lene
1	Dielectric strength (kV/mm)	48.2	37.7	35.5
2	Dielectric permeability at f = 60 Hz	3.7	1.95	2.26
3	Coefficient of dielectric losses tg δ at f = 60 Hz	0.0622	0.0003	0.0004
4	Volume resistivity (Ω . cm)	10^{13}	10^{17}	10^{17}
5	Surface resistivity (Ω cm/cm)	$1.2 \cdot 10^{15}$	10^{16}	10^{16}

serving to register the course of surges.

An electromagnetic voltmeter cl. 0.5 supplied from resistance divider (distributor) served to measure values of direct and alternating potentials. The error in measurements of direct and alternating potentials was of the order of 1%. Values of lightning surge potential and switching potential were measured by means of a spherical sparkmeter, whose maximal measurement error is 3%.

Outside the vacuum chamber there was placed a Video type camera coupled with magnetoscope, monitor and a photographic camera. 48

For studying the degree of degradation of the surface of investigated samples we used an electron microscope type SUPER MINI-SEM , produced by Japanese company JEOL, and an optical microscope.

Spectrographic analysis was done by means of a spectrograph type SPECORD 71 IR.

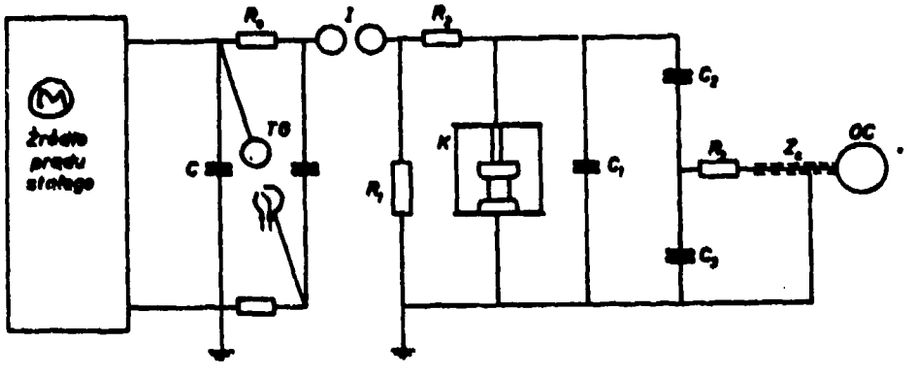

Figure 4.3. Generator of switching surges: TG- trigatron, I - spherical sparkmeter, K - vacuum chamber with system of electrodes and solid dielectric, C- generator capacity 0.25 μF, R - charging resistance 3.5 kΩ, R_1 - resistance forming the course of surge from 520 Ω to 600 kΩ, R_2 - resistance forming surge wave front from 5 kΩ to 100 kΩ, $Z_c = R_3$ - cable impedance 75 Ω, C_1 - load capacity 0.005 μF (not used for normal surge wave 1.2/50 μs), C_2 - divider capacity 0.0001 μF, C_3 - divider capacity 0.1 μF, M - D.C. source

4.2. EXPERIMENTAL PROCEDURE

It is a known fact that the method of joining the solid dielectric with electrode [71, 72] has a large influence on the pre-discharge mechanism and the flashover potential. Preparation of samples under uniform conditions and elimination of air space between solid dielectric and electrodes enables one to obtain results with relatively small scatter. According to many authors [36, 69] the lack of good contact between solid dielectric and electrode makes it impossible altogether to carry out reliable measurements. Hence, as was mentioned in Section 4.1, the investigated samples had silvered surfaces of contact with electrodes and there was a constant press applied to electrodes.

As follows from the above, different values of flashover potential may be obtained depending on the way of joining solid

dielectrics with electrodes, e.g., solid dielectrics may be even inserted into the electrode (Figure 2.5). However, at a good contact of solid dielectric with electrodes the scatter of measurement results should be small.

Preliminary experiments have shown that the time of degassing of the chamber with the sample, counting the time from the moment of obtaining vacuum to the moment of applying the test potential, has a large effect on value of potential of pre-flashover discharging and on the degradation of sample. For this reason, after placing sample in the chamber the whole system was subjected to degassing for the period of 24 hours at the pressure 133.322×10^{-6} Pa (10^{-6} Tr).

The investigated samples were made from synthetic materials which had relatively low melting temperatures, hence it was not possible to apply the technique of heating samples during degassing. At the time of measurements the temperature was 293 ± 2 K ($20 \pm 2^{\circ}$C).

Usually, the first measurements gave lower values of the flashover voltage. For this reason and in view of conditioning requirements it was decided that only after 10 flashovers the readings would be taken for 10 consecutive flashovers, which gave results with small scatter. An example of the increase of flashover potential as a function of consecutive readings is shown in Figure 4.4 and Table 4.2.

In order to obtain concordant and reproducible values of the flashover potential each new sample was conditioned by the application of direct or alternating potential of values somewhat above of which the pre-flashover discharging takes place, that is about 70% of flashover potential. This potential was maintained until the pre-flashover discharging completely subsided, for the period of 15 minutes. Next, the test potential, direct or alternating, was gradually raised by about 2 kV every

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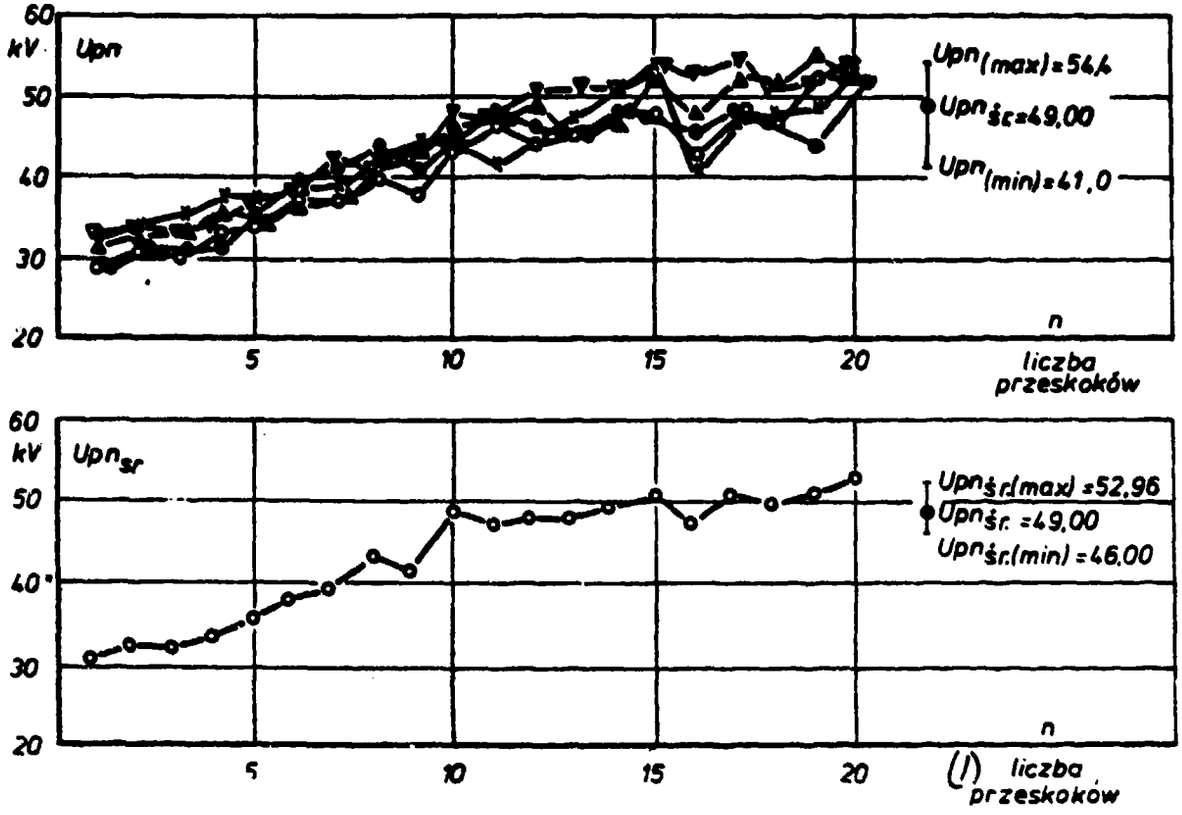

Fig. 4.4. Flashover voltage as a function of consecutive flashover for five various samples. Alternating potential, pressure 133.322×10^{-5} Pa (10^{-5} Tr), samples of polymethylmethacrylate 10 mm long (see table 4.2).
Key; (1) Number of flashovers.

Table 4.2. Flashover voltage as a function of consecutive flashovers for five various samples of polymethylmethacrylate 10 mm long. Alternating potential, conditioning with alternating potential.

(1) Kolejny przeskok n	(2) Napięcie przeskoku Upn, kV (3) Próbka ○	●	▲	×	▽	(4) Wartość średnia $Upn_{śr}$	
1	29,8	29,6	31,0	33,0	33,2	31,31	
2	31,4	31,6	32,8	33,6	33,4	32,56	
3	30,0	31,0	33,0	35,2	33,6	32,56	
4	33,2	31,2	35,0	35,0	34,0	33,68	$Upn_{śr} = \frac{\sum_{m=1}^{m=5} Upn}{5}$
5	33,8	35,6	33,6	38,8	37,0	35,76	
6	37,2	40,0	36,4	39,0	39,0	38,32	
7	37,0	41,0	38,0	39,6	42,0	39,52	
8	40,0	44,0	43,0	42,8	41,4	42,24	
9	38,8	40,8	43,6	44,0	42,0	41,84	
10	43,0	44,6	46,6	46,6	48,6	45,88	
11	46,6	49,0	47,0	42,0	48,0	46,52	$Up_{śr} = \frac{\sum_{n=1}^{n=20} Upn_{śr}}{10}$
12	44,0	46,6	49,2	45,0	50,4	47,08	
13	45,6	45,6	45,4	48,6	51,4	47,32	
14	47,4	49,0	46,6	51,0	51,4	49,08	$Upn_{śr(max)} = 52,96$
15	48,2	48,2	51,8	54,0	54,0	51,24	
16	43,0	46,0	47,0	41,0	53,0	46,00	$Up_{śr} = 49,00$
17	49,0	49,0	51,8	47,0	54,4	50,24	
18	47,0	48,0	51,2	47,8	51,0	49,00	$Upn_{śr(min)} = 46,00$
19	52,8	44,0	55,0	49,8	52,0	50,56	
20	52,6	52,0	52,0	54,2	54,0	52,96	

Key: (1) Consecutive flashover; (2) Flashover voltage; (3) Sample; (4) Average value.

second, until the flashover occurred.

In order to obtain reproducible results of measurements at normal surges and switching surges, the samples were first conditioned with direct or alternating potential in the same way as in the test with direct or alternating potential, that is to say they were allowed to have the first 10 flashowers using the direct or alternating potential. Next, 10 normal surges or switching surges were applied at each potential level in one-minute time intervals. The voltage was increased gradually by about 5% of the value of flashover potential, beginning at about 70% of the expected flashover potential, as is illustrated in Figures 4.5 and 4.6.

Experiments were performed on 5 samples for each length of sample and type of test potential. Ten measurements were made for each type of test potential, and thus the value of flashover potential for a given measurement point is determined as an average value from 50 measurements.

Figure 4.4 shows as an example the flashover voltage as a function of consecutive measurements for 5 different samples of polymethymethacrylate of length 10 mm.

4.3. TREATMENT OF EXPERIMENTAL RESULTS

Treatment of experimenteal results was based on statistical analysis [112] which permitted to obtain representative data.

The obtained results of the conducted studies of surface electric strength of solid dielectrics in vacuum are random events, characterizing distributions of variable random results of measurements (measurement domains). The obtained completed set of results for one measurement is a random sample from the general population.

General values obtained in measurements can be represented as:

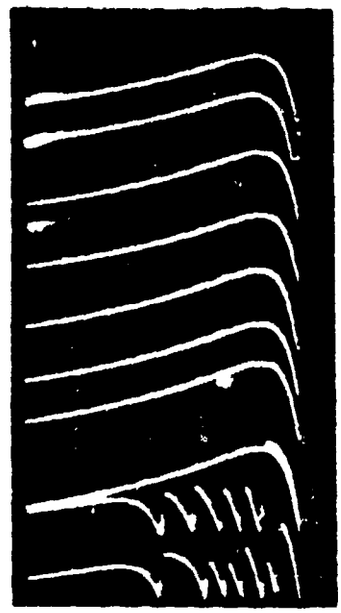

Figure 4.5 (left). Oscillogram of consecutive switching surges 50/250 μs, pressure 133.322x10^{-5}Pa (10^{-5} Tr), sample of polymethylmethacrylate 5 mm long.
Counting from top to bottom: 1 - 18.0 kV, first surge; 2 - 18.0 kV, tenth surge; 3 - 22.0 kV, first surge; 4 - 22.0 kV, tenth surge; 5 - 26.0 kV, first surge; 6 - 26.0 kV, tenth surge; 7 - 28.0 kV, first surge; 8 - 28.0 kV, tenth surge; 9 - 29.5 kV, first surge - - flashover; 10 - 29.5 kV, second surge - flashover

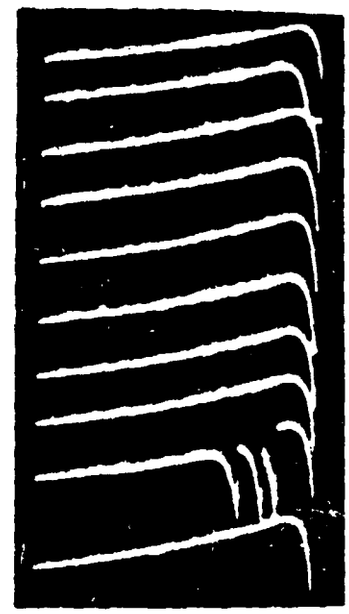

Figure 4.6 (right). Oscillogram of consecutive switching surges 80/700 μs, pressure 133.322x10^{-5}Pa (10^{-5} Tr), sample of polymethylmethacrylate 5 mm long.
Counting from top to bottom: 1 - 13.0 kV, first surge; 2 - 13.0 kV, tenth surge; 3 - 17.0 kV, first surge; 4 - 17.0 kV, tenth surge; 5 - 20.0 kV, first surge; 6 - 20.0 kV, tenth surge; 7 - 21.0 kV, first surge; 8 - 21.0 kV, tenth surge; 9 - 22.5 kV, first surge - - flashover; 10 - 22.5 kV, second surge

$$x_i = \mu + e + \varepsilon_i ,$$
$$x_i = \bar{x} + \varepsilon_i ,$$

where: x_i - value obtained in i-th measurement,
$\bar{x}$ - constant part of measured quantity,
μ - actual (real) value of measured quantity,
e - systematic error of measurement,
ε_i - accidental (random) error of measurement.

Appropriate apparatus, materials and methods of measurement were used to reduce systematic errors.

For consideration of random errors we took the model of the normal distribution of errors, since such type of distribution is taken as a rule in statistical analyses of the results of measurements in similar experiments.

For the accepted normal distribution of errors, the values of measurements x_i for each measurement nest will also be subject to normal distribution described by the function:

$$f(x_i) = \frac{1}{\sqrt{2\pi}s} \exp\left[-\frac{1}{2}\left(\frac{x_i - \bar{x}}{s}\right)^2\right],$$

where: s - standard deviation of errors.

The obtained results of measurements as a sample of general population do not provide the real values but they only supply information for their estimate.

Arithmetic mean was determined from a sample which is not limited by estimating the value of the expected population: 153

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i .$$

Unlimited estimators of variance were obtained from the formula:

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 ,$$

where: $\bar{x}$ - arithmetic mean of sample
x_i - value of i-th measurement
n - number of items in sample.

The level estimate was also made. It allows to determine confidence levels of the parameters of distribution, that is such levels around the values of measurement results that the probability that the expected value, and value of variance of general population s^2, would lie in this range, and the probability had a given value called the confidence level.

For the normal distribution of random variable of measurement, when the value of standard deviation (s) of the population is unknown and we only have its estimate, the confidence level is described by expression:

$$P\left(\bar{x} - t_p \frac{s}{\sqrt{n}} < E(x) < \bar{x} + t_p \frac{s}{\sqrt{n}}\right) = p$$

where: $E(x)$ - expected value,
t_p - random variable in t-Student distribution (the value of t_p is found in tables for the accepted $\alpha = 1-p$ and for degree of freedom $\nu = n-1$),
$\alpha = 1-p$ - level of significance,
p - confidence level.

We applied χ^2 statistics to check the hypothesis of the normal distribution of measurement results. To reject values of measurements considerably differing from other values we used the method of Dixon. This method assumes the normal distribution

of the results of measurements, and consists of lining the results in increasing order after rejecting the minimal values, and in decreasing order after rejecting the maximal values. Testing of the hypothesis about normal distribution of measurement results was done at the level of significance $\alpha = 0.05$. The obtained results gave no reason for rejecting the hypothesis.

Average values of measurement results are shown in graphs. In several cases the extreme values were rejected. Confidence ranges of average values of measurements lie within the maximal limits for the accepted levels of confidence:

$\alpha = 0{,}1$;	$p = 0{,}9$;	$0{,}977\ \bar{x} + 1{,}023\ \bar{x}$.
$\alpha = 0{,}05$;	$p = 0{,}95$;	$0{,}972\ \bar{x} + 1{,}028\ \bar{x}$.
$\alpha = 0{,}01$;	$p = 0{,}99$;	$0{,}962\ \bar{x} + 1{,}038\ \bar{x}$.

Confidence ranges for variance are, respectively: 54

$\alpha = 0{,}1$;	$0{,}7093\ s^2 + 1{,}377\ s^2$,
$\alpha = 0{,}05$;	$0{,}6604\ s^2 + 1{,}457\ s^2$,
$\alpha = 0{,}01$;	$0{,}5710\ s^2 + 1{,}622\ s^2$.

In this work, on selected graphs we are giving relations between values arising from measurements by means of analytical equations. The mathematical form of dependence between empirical variables is not known. It was necessary, therefore, not only to determine equation constants but first to choose the most suitable form of the equation.

When choosing the form of an empirical equation representing the experimental data we tried to find a equation expressing best the relations between variables, having physical reason, and also

having possibly the smallest number of constants. The method of least squares was applied to determine constants of the equation.

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5. RESULTS OF OUR INVESTIGATIONS OF THE SURFACE ELECTRIC STRENGTH OF THERMOPLASTIC MATERIALS IN VACUUM

5.1. EFFECT OF PRESSURE ON FLASHOVER POTENTIAL

As was already mentioned in Section 2.3.1., Ramm [100] observed the existance of the effect of pressure, in the range from 133.322×10^{-6} Pa to 133.322×10^{-2} Pa (from 10^{-6} to 10^{-2} Tr), on electric strength of the system solid dielectric-vacuum. Ramm did not carry out detailed investigations, but he noted only a change of electric strength of pass insulator in vacuum as a function of pressure.

For determination of electric strength of the system solid dielectric-vacuum we measured and then analyzed the effect of pressure in the range from 133.322×10^{-6} Pa to 133.322×10^{-2} Pa (from 10^{-6} to 10^{-2} Tr). Samples from polymethylmethacrylate, polytetrafluoroethylene and polyethylene of length 5, 10, 15 and 20 mm were used in investigations. Measurements were carried out using the following potentials: direct, alternating 60 Hz, surge 1.2/50 μs, and switching surge 50/250 μs and 400/2000 μs. In order to obtain reproducibility of results of investigations we carried out conditioning of samples according to Section 4.2.

Figure 5.1 presents dependence of flashover potential at direct potential as a function of pressure for samples from polymethylmethacrylate of length from 5 to 20 mm. For all the lengths of investigated samples the flashover voltage showed the tendency of going down as the pressure increased from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} to 10^{-4} Tr). The lowering of electric strength of the system in this range of pressure is

rather small. Then the flashover voltage increases strongly and reaches the maximum value at the pressure of about 666.61×10^{-4} Pa (5×10^{-4} Tr). In turn, the flashover voltage goes down and falls to the value nearly zero.

Measurement of the electric strength of systems at pressures from 133.322×10^{-3} Pa to 133.322×10^{-2} Pa (from 10^{-3} to 10^{-2} Tr) is practically impossible, since already at several kV there occurs an incomplete discharge and the whole interior of the chamber glows with light-blue color. The intensity of this glow increases with the increase of applied potential, and the most pronounced glow appears on the surface of solid dielectric, particularly at the site of the dielectric-electrode junction.

An attempt was made to utilize this phenomenon of glowing for the conditioning of samples. Such conditioning of samples by means of glow resulted in a reduction of the scatter of measurement. However, this method was abandoned because of difficulties with determining unambiguosly the parameters of conditioning.

Measurements of electric strength of the system solid dielectric-vacuum were intended to be carried out for various types of supply potential. Hence we performed measurements of flashover voltage of investigated systems as a function of pressure for all types of test potentials. Figure 5.2 shows results of conducted investigations of flashover voltage as a function of pressure for a sample from polymethylmethacrylate 10 mm long.

Dependence of flashover potential as a function of pressure at alernating test potential is the same as at direct potential. For the surge wave 1.2/50 μs the flashover voltage has a constant value in the range of pressure from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} to 10^{-4} Tr), and then falls down at the pressure 133.322×10^{-3} Pa (10^{-3} Tr), but does not show the characteristic rise. For the investigated switching surges

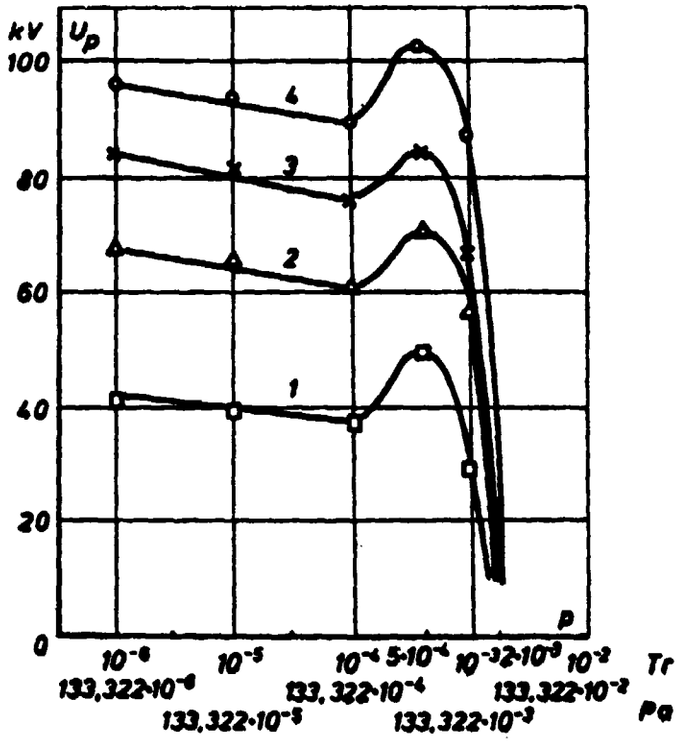

Figure 5.1. Flashover voltage as a function of pressure for samples from polymethylmethacrylate. Direct potential.
1 - sample 5 mm long, 2 - sample 10 mm long,
3 - sample 15 mm long, 4 - sample 20 mm long

the flashover voltage has a constant value in the pressure range from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} to 10^{-4} Tr). The characteristic rise of strength at the pressure 666.610×10^{-4} Pa (5×10^{-4} Tr) does occur for switching surges, but this rise is very small.

Experiments were performed on samples from polytetrafluoroethylene and polyethylene and the same dependence of flashover voltage as a function of pressure was found as in the case of samples from polymethylmethacrylate.

Figure 5.3 shows the course of switching surge 400/2000 μs

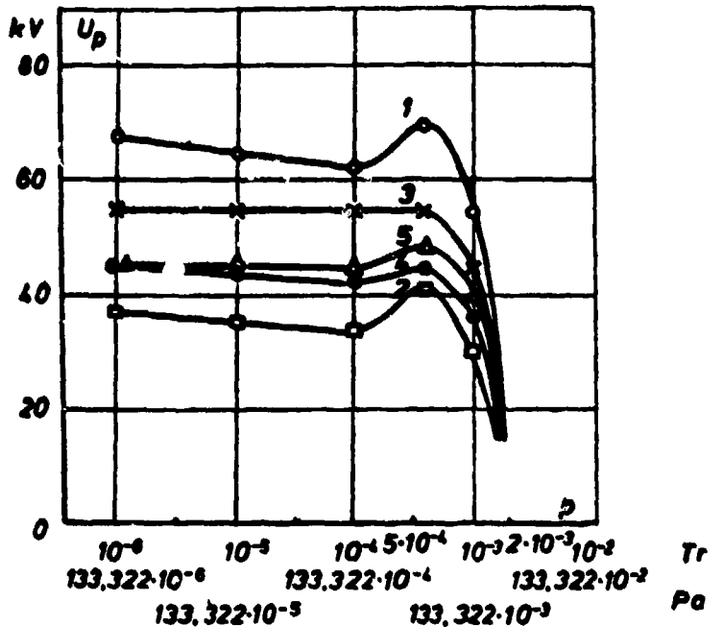

Figure 5.2. Flashover voltage as a function of pressure for samples from polymethylmethacrylate, at various types of potentials. Length of sample 10 mm; 1 - direct (constant) potential; 2 - alternating potential 60 Hz; 3 - normal surge 1.2/50 μs; 4 - switching surge 50/250 μs; 5 - switching surge 400/2000 μs

during flashover at various pressures, for samples of polytetrafluoroethylene 5 mm long. The voltage of switching surge is considerably higher than the flashover voltage, hence the first ignition occurs at the surge wave front, and there are several ignitions in the period of one switching surge. The flashover voltage at the pressure 133.322×10^{-6} Pa (10^{-6} Tr), Figure 5.3a, and at the pressure 133.322×10^{-4} Pa (10^{-4} Tr), Figure 5.3b, is practically the same. The lowering of flashover potential occurs at the pressure 133.322×10^{-3} Pa (10^{-3} Tr), Figure 5.3c.

Figure 5.4 illustrates good reproducibility of results. It shows three consecutive switching surges. The flashover voltage remains constant at a given pressure during first flashovers, until the effect of sample degradation appears.

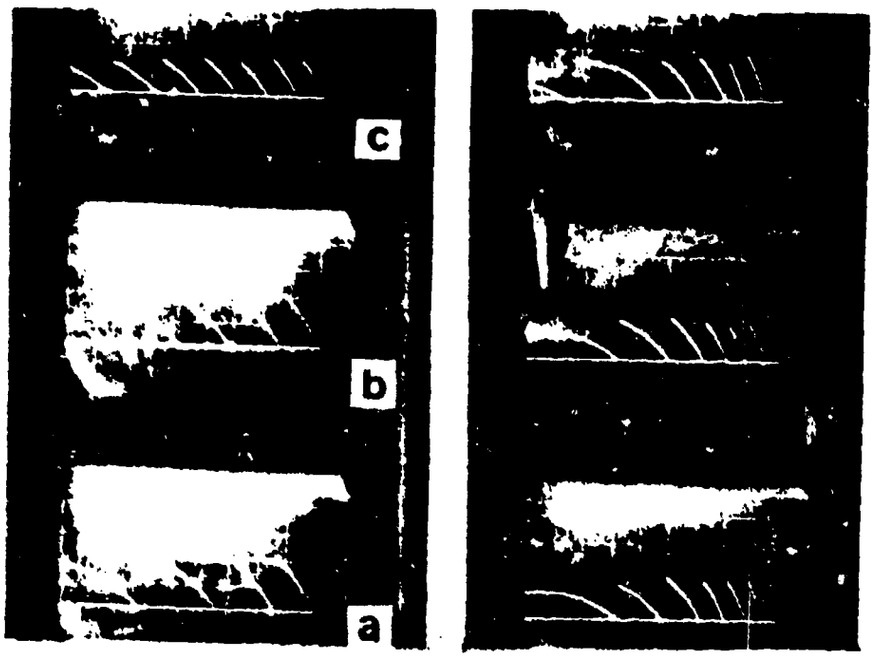

Figure 5.3 (left). Oscillograms of switching surge 400/2000 μs at the time of flashover. Polytetrafluoroethylene sample 5 mm long. Scale: 100 μs/cm, 50 V/cm.

a) pressure 133.322×10^{-6} Pa (10^{-6} Tr),
b) pressure 133.322×10^{-4} Pa (10^{-4} Tr),
c) pressure 133.322×10^{-3} Pa (10^{-3} Tr).

Figure 5.4 (right). Oscillograms of switching surge 400/2000 μs at the time of flashover. Polytetrafluoroethylene sample 5 mm long. Scale: 200 μs/cm, 50 V/cm.

Pressure 133.322×10^{-5} Pa (10^{-5} Tr).

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The conducted experiments confirm that the surge potential of flashover for the system solid dielectric-vacuum in the range of pressure from 133.322×10^{-6} Pa to 133.322×10^{-4} Pa (from 10^{-6} Tr to 10^{-4} Tr) does not undergo change.

The above statement allows to carry out investigations of the electric strength of the system during the occurrence of pre-flashover discharges, which change the pressure in the chamber only to a small degree. The pressure at which such experiments were conducted was chosen to be 133.322×10^{-5} Pa (10^{-5} Tr), since efficiency of the system of pumps was of this order that it allowed to maintain constant pressure of 133.322×10^{-5} Pa (10^{-5} Tr) during the not too strong pre-flashover discharges.

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5.2. EFFECT OF METALLIZATION OF SURFACE OF THE DIELECTRIC-ELECTRODE JUNCTION ON THE VALUE OF FLASHOVER VOLTAGE

Many investigators consider that, from the viewpoint of the development of flashover, of particular importance are conditions at the cathode and on surface of solid dielectric-cathode junctions [14, 36, 37, 71, 72, 76, 96]. It was found that when the surface of cathode is rough the flashover potential along the sample is considerably reduced, whereas the effect of the roughness of anode is small [14]. This phenomenon is connected with nonuniform distribution of the potential of electric field.

Nonuniformity of the distribution of electric fields is caused by:

1) appearance of crevices on the surface of solid dielectrics, which causes an increase of the potential of fields in the crevice (crack); in places of insufficient contact between the sample and electrode (in crevices) there is a manyfold increase of the field potential, depending on dielectric permeability of the solid dielectric,

2) presence of impurities on surface of solid dielectrics with different surface resistance, which causes various local drops of potential during the flow of applied current,
3) presence of impurities in solid dielectrics with different dielectric permeability, which changes the field distribution, causing local discharges,
4) nonuniform distribution of charges on surface of solid dielectrics under the effect of high-voltage polarization of dielectric and secondary emission of electrons.

The strongest effect on nonuniformity of distribution of electric field is exerted by the presence of crevices (cracks) at the solid dielectric-electrode junction. In order to eliminate these crevices, surfaces of samples in contact with electrodes in investigations conducted by the author were metallized (Figure 5.5).

The effect of metallization of the surface of contact of the sample with electrodes on the flashover voltage will be illustrated on example of measurements of flashover voltage on samples from polymethylmethacrylate. Metallization of the surface of samples was done by evaporation of silver in vacuum. Before measurements, the samples were conditioned with alternating potential. Investigations were performed using three types of test potential: direct, alternating and surge potential.

Figure 5.6 shows the surface strength as a function of the number of flashovers for 5 metallized samples and 5 nonmetallized samples from polymethylmethacrylate of length 20 mm. The strength of both metallized and nonmetallized samples increases as the number of flashovers increases. Values of flashover voltage for nonmetallized samples have a considerably higher scatter, which makes it difficult to obtain reproducible results of studies. The flashover potential of metallized samples is lower than that of nonmetallized samples. After 10 flashovers, the flashover voltage

[61]

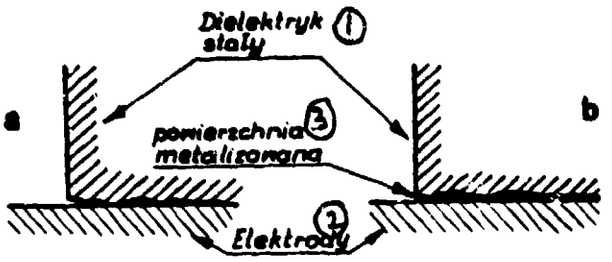

Figure 5.5. Junction of electrode with solid dielectric:
a) nonmetallized sample, b) metallized sample.
1 - solid dielectric, 2 - electrodes,
3 - metallized surface.

becomes stabilized.

In turn, Figure 5.7 presents average values of the flashover voltage for 5 samples metallized and nonmetallized, of the length 10, 15, 20 and 30 mm. All these experiments indicate that the surface strength of metallized samples is lower than the strength of nonmetallized samples.

Figure 5.8 shows the voltage of flashover along the surface of solid dielectrics as a function of the length of sample. The points on the graph represent average values of 10 last flashovers counting from eleventh to twentieth, for 5 nonmetallized and 5 metallized samples of given length. The graph shows that for all the investigated lengths of samples the flashover potential of nonmetallized samples is higher than that of metallized samples.

For better presentation of the effect of metallized surface of solid dielectric-electrode junction on surface strength, the author introduces the coefficient η, called the coefficient of lowering surface strength of solid dielectric because of

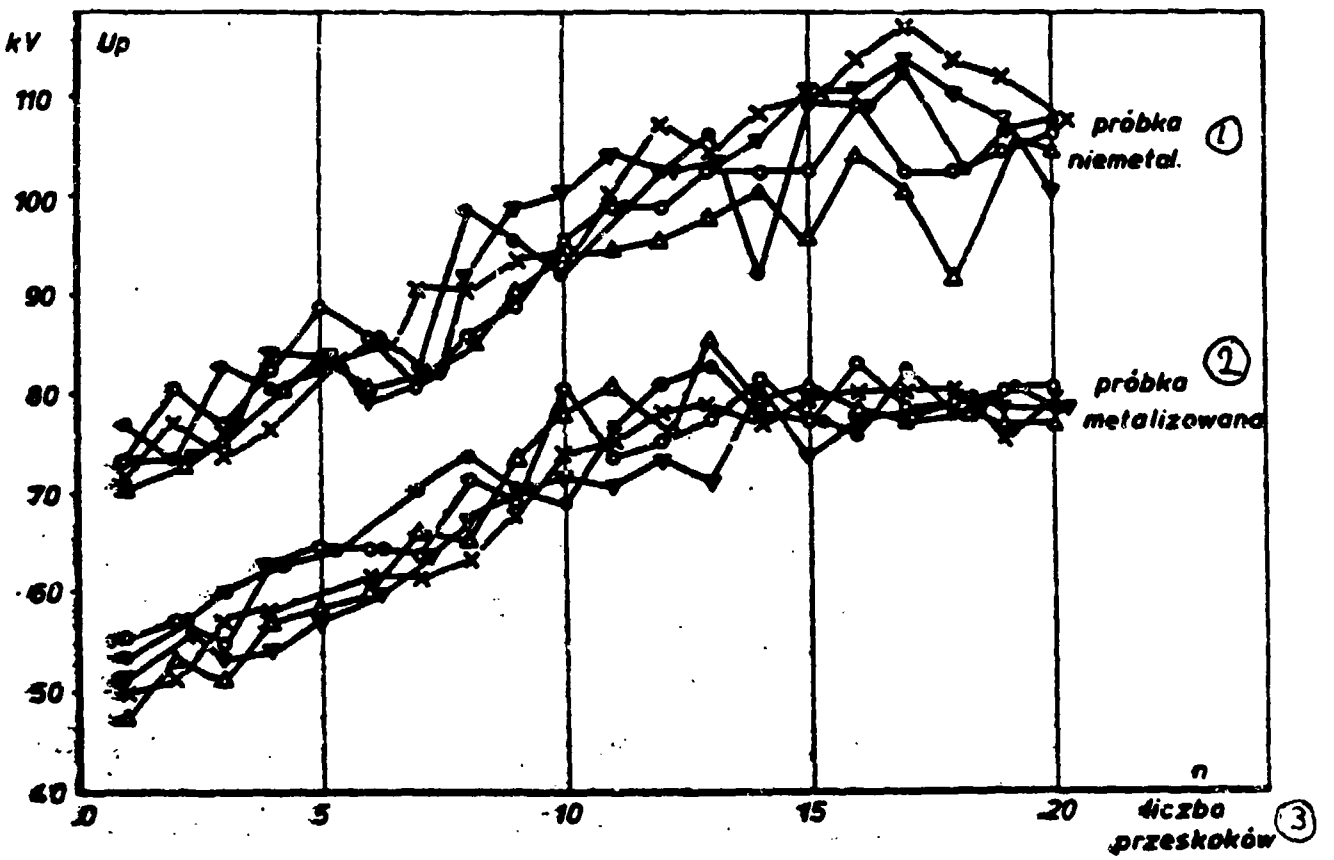

Fig. 5.6. Surface strength of 5 metallized samples and 5 non-metallized samples from polymethylmethacrylate as a function of the number of flashovers. Length of sample 20 mm. Alternating potential.
Key: (1) Nonmetallized sample, 2) metallized sample; (3) Number of flashovers.

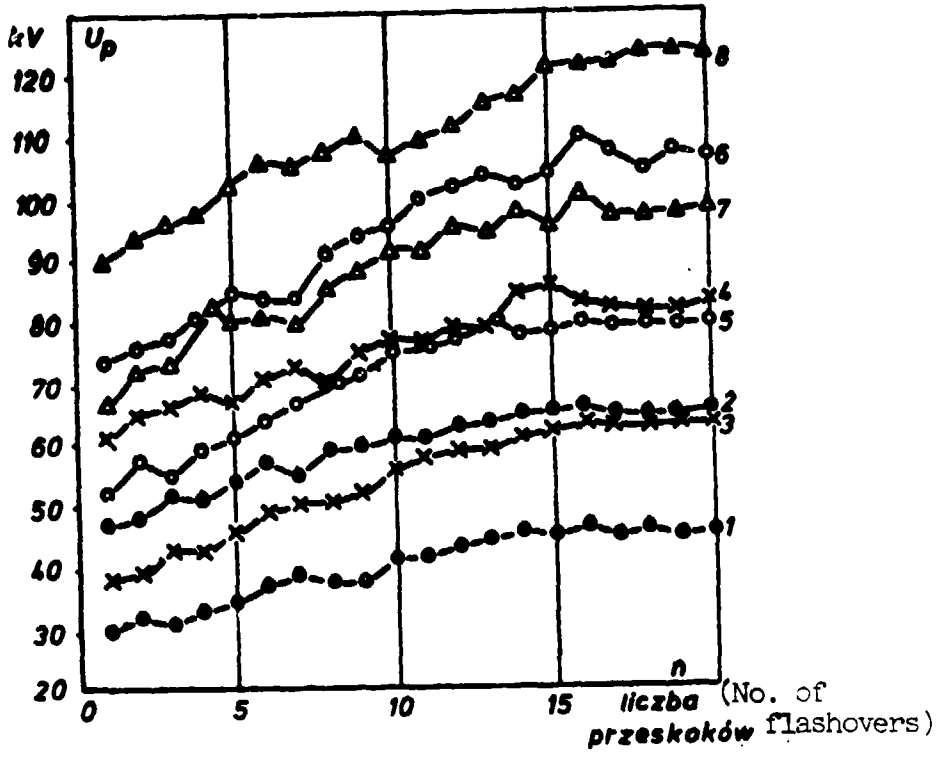

Figure 5.7. Average surface strength of 5 samples from polymethylmethacrylate as a function of the number of flashovers (abscissa). Alternating potential.
1, 3, 5, 7 - metallized samples; 2, 4, 6, 8 - nonmetallized samples; 1, 2 - samples 10 mm long; 3, 4 - 15 mm long; 5, 6 - 20 mm long; 7, 8 - samples 30 mm long

metallization of the surface of solid dielectric.

The coefficient η is given the form:

$$\eta = 1 - \frac{x_{\text{śr.mat}}}{x_{\text{śr pierwot.}}},$$

where: $x_{sr\ met.}$ - average value of flashover voltage for 5 metallized samples of solid dielectric of a given length,

$x_{sr\ niemet.}$ - average value of flashover voltage for 5 identical nonmetallized samples.

It is seen that the flashover voltage for metallized samples at alternating potential (Figure 5.9) is lower than the flashover voltage for nonmetallized samples, by about 30% for samples 10 mm long and by about 20% for samples of length 30 mm. With increase of the length of solid dielectrics the effect of metallization of the surface of solid dielectric becomes smaller and smaller. 163

In general, discharges begin at the solid dielectric-cathode junction, it means there where the electric field intensity is the greatest. The source of emission of electrons, which initiate the discharges, are microedges (micropeaks). These microedges have the highest effect at the border of solid dielectrics where they seriously reduce the surface strength. A thin layer of silver on the surface of solid dielectrics provides microedges from which the field emission of electrons ensues.

Thus, metallization of the surface of solid dielectrics eliminates crevices between the solid dielectric and electrode, but it also introduces microedges at the site of solid dielectric-electrode junction. The presence of microedges has a considerable effect on lowering of surface strength. As the length of solid dielectric increases, the value of flashover voltage of metallized samples approaches the value of voltage of nonmetallized samples.

Studies of the effect of metallization of the surface of solid dielectric on surface strength at direct(constant) potential and surge potential reveal a similar tendency of changes of the coefficient (Figure 5.10 and Figure 5.11) as at alternating potential.

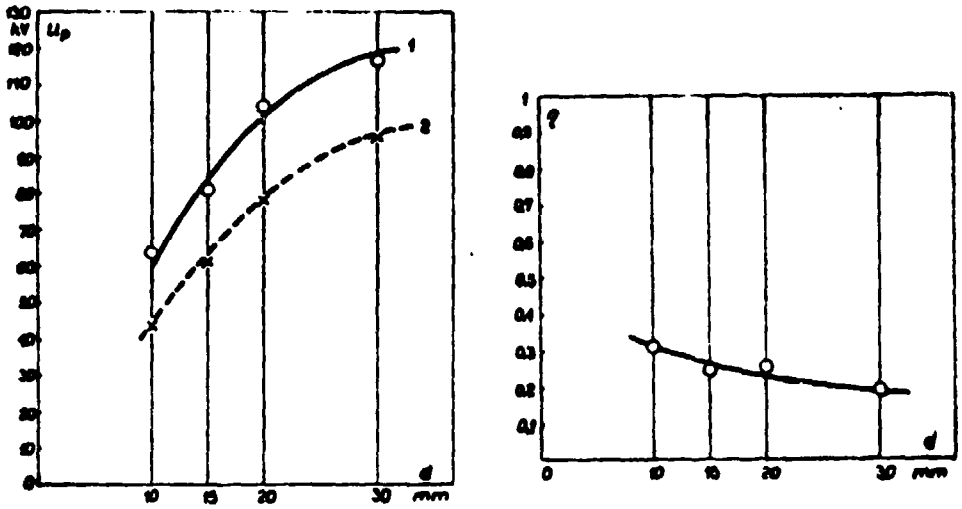

Figure 5.8 (left). Flashover voltage as a function of the length of sample from polymethylmethacrylate. Alternating potential; 1 - nonmetallized samples; 2 - metallized samples.

Figure 5.9 (right). Coefficient of lowering of surface strength because of metallization of the surface of sample-electrode junction as a function of the length of sample. Sample from polymethylmethacrylate. Alternating potential.

As a result of metallization of the surface of solid dielectrics, the surface strength at direct potential decreased by about 40% for samples 10 mm long and by about 30% for samples with length of 30 mm. The lowering of strength at direct potential is greater than at alternating potential. Because of a strong electric field, silver ions migrate in one direction on the surface of solid dielectrics. It may be assumed that during studies at direct potential some permanent changes have occurred at the surface of solid dielectric, and that silver ions have changed the charge distribution on the surface of solid dielectrics.

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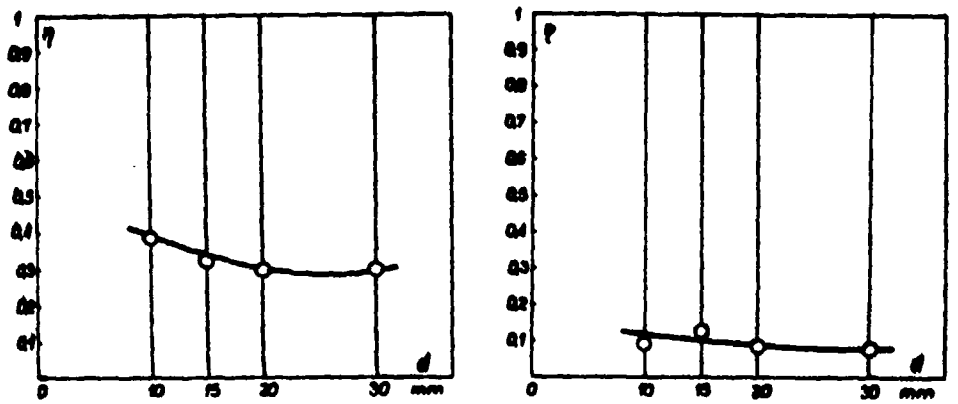

Figure 5.10 (left). Coefficient of lowering of surface strength because of metallization of the surface of the sample-electrode junction as a function of sample length. Sample from polymethylmethacrylate. Direct potential.

Figure 5.11 (right). Coefficient of lowering of surface strength because of metallization of the surface of the sample-electrode junction as a function of sample length. Sample from polymethylmethacrylate. Surge potential.

The lowering of surface strength because of metallization of surface of solid dielectrics at surge potential for a given length of samples from 10 mm to 30 mm amounts to 8%. This is caused by the fact that for this type of potential the charge on surfaces of solid dielectric created by the secondary emission of electrons will have no effect. Hence, at the surge potential the effect of space charge, arising as a result of field emission from microedges (silver layer), on the flashover potential is small since the space charge has no time to form.

All further experiments in this work will be carried out on samples with metallized surface of dielectric junction, because of a smaller scatter of measurement results than with nonmetallized samples.

5.3. EFFECT OF CONDITIONING ON VALUE OF FLASHOVER VOLTAGE

The majority of investigators of this problem concluded that measurement results of the value of flashover voltage depend strongly on the method of conditioning of sample. So far, however, no standardized way of conditioning has been defined.

In some works [25, 59, 61, 102, 107] it was shown that the conditioning of electrodes is the most important factor deciding about flashover voltage in the system of electrodes in vacuum. Much less information is available concerning the effect of electrodes and their conditioning on flashover potential when a solid dielectric is placed between the electrodes in vacuum. Some conducted experiments indicated that conditioning of the surface of solid dielectric has decisive effect on the value of flashover voltage, whereas the effect of conditioning of the surface of electrodes is relatively small, as long as the surface of electrodes remains smooth and clean. Conditioning of the surface of samples has also a strong effect on intensity of pre-flashover discharges, which increases as the length of solid dielectric increases.

On the basis of the literature review and our investigations it was concluded that the following parameters of conditioning exert large effects on the surface strength of solid dielectrics in vacuum:

1) value of pressure and time of pressure conditioning,
2) type of conditioning potential,
3) value of potential and time of potential conditioning,
4) number of initial flashovers and time between them.

As stated in Section 4.2, investigations of surface strength of solid dielectrics in vacuum were conducted at the pressure 133.322×10^{-5} Pa (10^{-5} Tr), on the basis of studies of surface strength as a function of pressure, described in Section 5.1. For the conditioning pressure we adopted 133.322×10^{-6} Pa (10^{-6} Tr),

which could be obtained with ease by our system of pumps. Measurements of surface strength after conditioning of samples at higher pressure were characterized by the occurrence of more intense pre-flashover discharges than after conditioning at the pressure 133.322×10^{-6} Pa.

Preliminary experiments showed that not only the pressure of conditioning but also the time of conditioning at a given pressure have effect on the value of initial voltage for pre-flashover discharges, the intensity of these discharges, and the surface strength. On the basis of a number of experiments it was established that for the investigated materials the value of initial voltage for pre-flashover discharges and of surface strength becomes stabilized at the pressure 133.322×10^{-6} Pa (10^{-6} Tr) when the time of conditioning is longer than 18 hours. In order to obtain uniformly stabilized effect of pressure conditioning we adopted for further studies the time of conditioning 24 hours at the pressure 133.322×10^{-6} Pa (10^{-6} Tr).

After the first flashovers new samples showed a lower value of the voltage of flashover along the surface of solid dielectric, and values of voltage of consecutive flashovers showed large differences. Only after a few flashovers the value of flashover potential exhibited tendency to become stabilized.

The effect of conditioning by means of flashovers, shown in Figure 5.12, gives consecutive values of flashover potential at direct potential (d.c.) obtained for a sample from polymethylmethacrylate 5 mm long. These experiments were performed after keeping the sample in vacuum at 133.322×10^{-6} Pa (10^{-6} Tr) for the period of 24 hours, i.e., after the accepted pressure conditioning.

The value of flashover voltage increases as the number of flashovers increases, which indicates the fact that the conditioning also takes place throughout the flashovers. After ten flashovers the surface strength became constant, hence we decided that for calculation of the average value for a given sample we shall

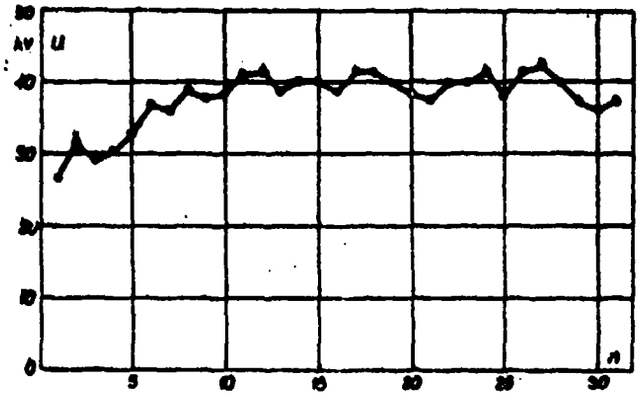

Figure 5.12. Flashover voltage as a function of consecutive flashovers (abscissa). Direct potential (d.c.), sample from polymethylmethacrylate 5 mm long, pressure 133.322x10^{-5} Pa (10^{-5} Tr).

consider values of potential from 11 to 20 flashover. Earlier flashovers occur at lower voltages which is caused probably by small impurities or uneven spots on the surface of the solid dielectric or electrode.

Further measurements have shown that the value of flashover voltage depends also on the time of interval between consecutive application of potential. If the time of interval was about one minute, the next values of flashover voltage were lower, and in some cases even be[illegible] 50% of the value of previous flashover voltage. In order to [illegible]tain reproducible results of measurements at direct (d.c.) pote[illegible]al and alternating (a.c.) potential, it was necessary to prolong the interval between consecutive application of potential to 10 minutes. Such a long period without potential suggests a possibility of the action of space charge, accumulating on the surface of investigated samples, on the lowering of value of flashover voltage.

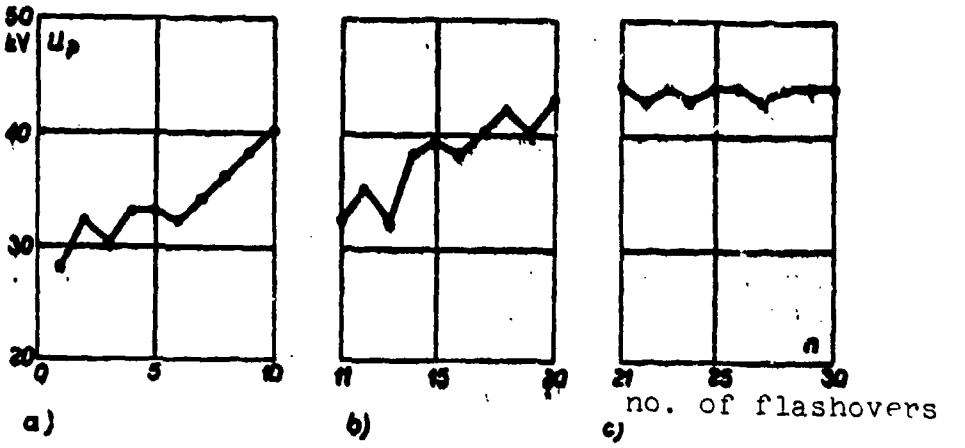

Figure 5.13. Consecutive values of flashover voltage at direct potential along polyethylene sample 5 mm long.
a) unconditioned sample, after placing the sample for a period of 24 hours at 133.322×10^{-5} Pa,
b) interval in measurements for 24 hours, sample placed in vacuum 133.322×10^{-6} Pa,
c) interval in measurements for 24 hours, sample conditioned with alternating potential of 20 kV for the period of 30 minutes

With lightning surge potential and simulated switching overvoltages, measurements have shown also a considerable scatter of the value of flashover voltage for unconditioned samples. The occurrence of pre-flashover discharges was also observed at surge potentials. Their presence could be evidenced by a temporary rise in pressure in the chamber, and by a glow during pre-flashover discharges. Similarly as before, in order to obtain reproducible results of measurements, before the application of surge and switching surge potential, samples were conditioned with direct or alternating potential in the same way as before the test with d.c. or a.c. potentials.

In order to determine whether the sample retains its acquired surface strength as a result of conditioning throughout

the flashovers, we carried out experiments which are illustrated in Figure 5.13. After the first ten flashovers the measurements were interrupted and the sample was left in vacuum for the next 24 hours. Then measurements were continued, and it was found that the flashover voltage for the first flashovers was lower after this interval (Figure 5.13b), evidencing a partial loss of properties imparted by conditioning. For this reason, after conditioning one should not make any interruptions (intervals) in a series of experiments.

The effect of the type of potential on conditioning is shown in Figure 5.13c. After consecutive 10 flashovers at direct potential, that is together after 20 flashovers, the experiment was interrupted again for the period of 24 hours, the sample remaining in vacuum without application of potential. In turn, alternating potential of the value of 20 kV was supplied to the sample for the period of 30 minutes. The next ten flashovers at direct potential are shown in Figure 5.13c. The value of flashover voltage has not changed in comparison with previous value, and remained constant considering rather small scatter.

Studies of surface strength at alternating potential indicated that one can get different values of flashover voltage when conditioning is done with alternating instead of direct potential. To confirm the effect of the type of potential on conditioning parameters we compared the conditioning of samples by means of direct and alternating potentials.

The effect of the type of conditioning potential on flashover voltage is illustrated in Figure 5.14. The graph shows flashover voltage at surge potential 1.2/50 μs for ten consecutive flashovers after the application of conditioning with direct potential (d.c.) or alternating potential (a.c.). The conditioning by means of direct or alternating potential consisted of raising potential by 2 kV every minute to the value of about 70% of the expected flashover voltage. The potential

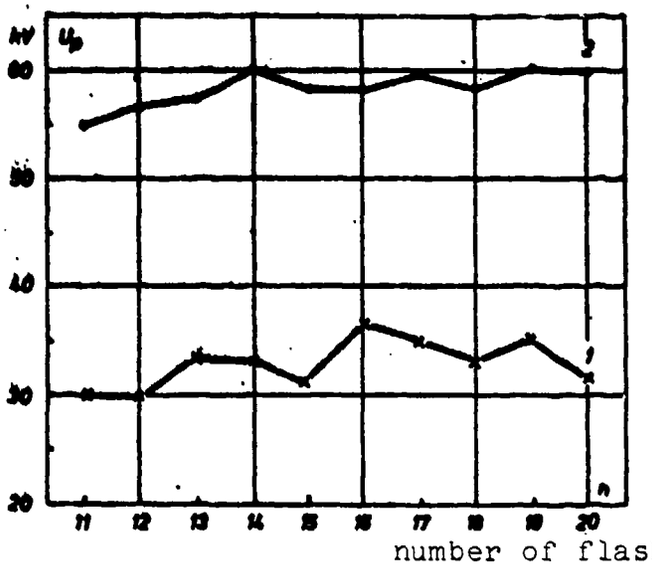

Figure 5.14. Effect of the type of conditioning potential and of 10 flashovers at the given conditioning potential on the test surge 1.2/50 μs flashover voltage. Polyethylene sample 5 mm long; 1 - sample conditioned with direct potential, 2 - sample conditioned with alternating potential.
Ordinate: U_p, kV; abscissa: n, number of flashovers

was maintained for 15 minutes, and then was raised to 10 flashovers still at the direct or alternating potential, respectively. In turn, surge potential 1.2/50 μs was applied to the sample and its value was raised up to the flashover. Surges were applied to samples every 1 minute. No repeat conditioning with d.c. or a.c. potential was done after each flashover.

As is seen from Figure 5.14 the application of alternating potential for conditioning is more effective than of direct potential, and a steady value of flashover voltage was attained after 5-6 flashovers. It was observed that flashover voltage, determined on the basis of values from 11-th to 20-th flashover,

has a higher value when the conditioning of sample was done with alternating potential.

The effect of conditioning with direct potential and alternating potential on the value of flashover voltage was also checked on samples from polytetrafluoroethylene (Teflon), and results of studies of flashover voltage as a function of the length of sample are presented in Figure 5.15 and Appendix 1. The graph shows the effect of conditioning with direct potential and alternating potential not only on the surge voltage of flashover but also on the flashover voltage at direct potential and alternating potential. Each point in Figure 5.15 represents an average value for 5 samples. The method of conditioning was the same as that given for Figure 5.14.

As is seen from Figure 5.15, conditioning by means of alternating potential has a distinct effect on the value of flashover voltage, particularly in the case of surge potential, for which the flashover voltage obtained after conditioning with alternating potential is nearly twice as high as the flashover voltage of the same samples conditioned with direct potential. The effect of conditioning with alternating potential is even clearer for samples from polytetrafluoroethylene (Teflon) than for samples of polyethylene.

Comparison of potential conditioning at various types of potential leads to the conclusion that alternating potential causes the most effective conditioning and leads to the most constant value of flashover voltage.

The effects of conditioning with various types of potential, various values of voltages, and various time of conditioning, can be explained by changes of the state of surface of solid dielectric caused by pre-flashover discharging. On the one hand, pre-flashover discharges cause desorption of gas; on the other hand, they are the cause of deposition of electrode

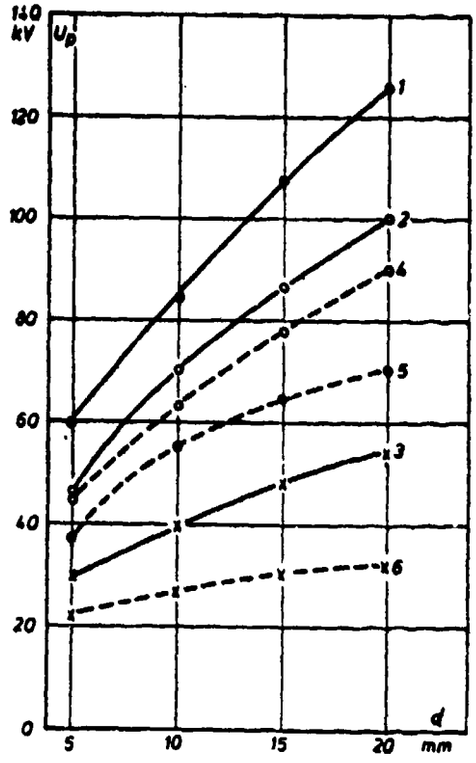

Figure 5.15. Flashover voltage at d.c. potential, a.c. potential and surge potential as a function of the length of sample for polytetrafluoroethylene (Teflon) after conditioning with d.c. and a.c. potential.

1 ——— Surge 1.2/50 μs (a.c. conditioning)
2 ——— d.c. potential (a.c. conditioning)
3 ——— a.c. potential (a.c. conditioning)
4 - - - - - d.c. potential (d.c. conditioning)
5 - - - - - surge 1.2/50 μs (d.c. conditioning)
6 - - - - - a.c. potential (d.c. conditioning)

material, and they result in formation of a thin carbon layer. Studies [16] have shown that the coefficient of secondary emission decreases as a function of the number of flashovers (Figure 2.10). Value of the coefficient of secondary emission will, therefore, change with conditions of potential conditioning. Flashover voltage depends on the coefficient of secondary emission hence flashover voltage is a function of parameters of potential conditioning. When parameters of potential conditioning change, the obtained values of flashover voltage will be different, but general relations will not change.

With d.c. and a.c. potential, the occurrence of pre-flashover discharges was observed on all new unconditioned samples at a voltage exceeding about 50% of flashover voltage; these discharges were seen both at the site of junction of electrodes with solid dielectric and on the surface of solid dielectrics.

In the case of d.c. potential, the intensity of pre-flashover discharging was the highest in the proximity of the anode. These discharges were characterized visually by the form of glow, and were disappearing with time. The frequency of their occurrence decreased with the time of the application of potential and usually after a few minutes these discharges completely disappeared.

One could observe also a series of discharges which began on the surface of solid dielectric and ended at some other point of the surface of dielectric without closing the gap between the electrodes. Such discharges were probably connected with the surface charge on solid dielectrics. Both the intensity and frequency of occurrence of discharges starting on the surface of solid dielectric increased with the length and roughness of outer surface of solid dielectric. Generally it is assumed that the action of high voltage leads to gradual removal of roughness of outer surface of solid dielectrics.

Samples subjected to action of a.c. potential had a stronger intensity of pre-flashover discharges than identical samples at d.c. potential. For samples of length 10 mm and longer, pre-flashover ischarges keep occurring until the time when the potential reaches the value of flashover voltage.

5.4. EFFECT OF THE LENGTH OF SAMPLE ON VALUE OF FLASHOVER POTENTIAL

One of the significant factors deciding the surface strength of solid dielectrics in vacuum is the length of sample. Studies indicate that the effect of the length of sample of solid dielectric on flashover voltage is dependent on the type of potential .

Values of flashover voltage as a function of the length of sample from polymethylmethacrylate are presented in Appendix 2 and in Figure 5.16, which shows surface strength of the investigated system at direct potential, alternating potential 60 Hz, surge potential 1.5/50 μs, and switching surges with different periods of time of the surge wave front. Values of flashover voltage are average values of results obtained for 5 samples, following the procedure given in Section 4.2. For each type of potential the flashover voltage increased with the length of the investigated sample. However, this increase of flashover voltage as a function of sample length is different for particular types of potential.

As follows from Figure 5.16, the percentage increase of flashover voltage with increase of the length of sample is the smallest for alternating potential. For switching surges the increase of flashover voltage becomes larger with shorter periods of time of the surge wave front. The largest increase of flashover voltage as a function of the length of sample was found to be for surge potential 1.2/50 μs.

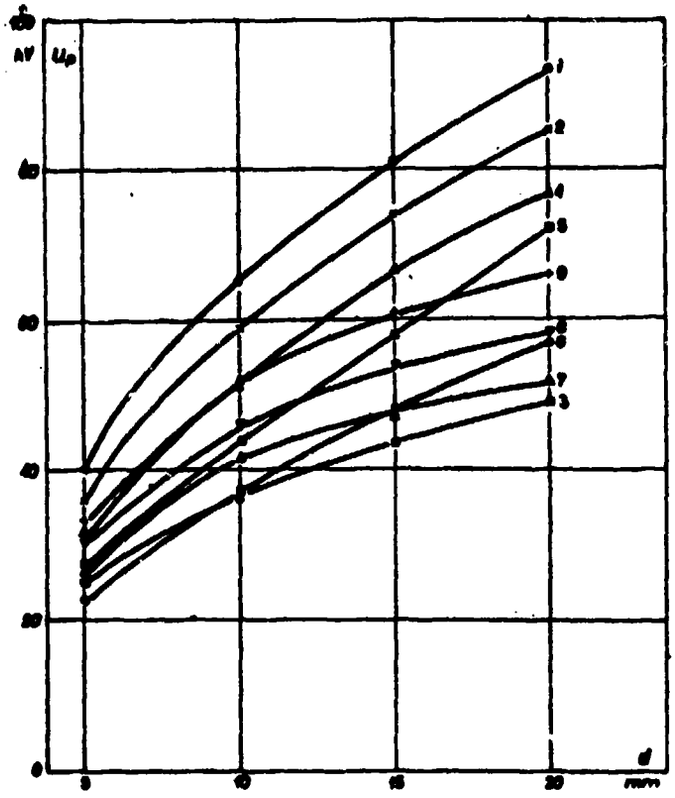

Figure 5.16. Flashover voltage as a function of the length of solid dielectric for various types of potential. Sample from polymethylmethacrylate, conditioned with direct potential.

1 - direct potential
2 - normal surge 1.2/50 μs
3 - alternating potential 60 Hz
4 - switching surge 35/80 μs
5 - switching surge 50/250 μs
6 - switching surge 80/700 μs
7 - switching surge 150/1800 μs
8 - switching surge 400/2000 μs
9 - switching surge 600/3000 μs

All the investigated samples which had been conditioned with direct potential showed the highest flashover voltage at direct potential. The conditioning with direct potential causes the appearance of a path of least resistance on the surface of solid dielectrics, and for this reason the surge voltage of flashover is lower than the flashover voltage at direct potential.

Appendix 2 gives the obtained relations describing the flashover potential as a function of the length of sample for various types of potentials, and lists values of the flashover voltage calculated using the derived equation.

The obtained equations, given in Appendix 2 and further in Appendices 3 to 9, are approximated by equation of the type:

$$Y = a\,x^{b} \qquad (5.1)$$

that is

$$U_p = \alpha_1 d^{\alpha_2}$$

where: U_p - flashover potential
d - length of sample
$\alpha_1 \alpha_2$ - constants.

This type of equation represents best the obtained results of investigation.

The calculated values of flashover voltage, using the derived equation, lie within a 90-percent confidence level. Analysis of equations given in Appendices 2 to 9 shows that surface strength at direct and surge potentials is a function of the product of approximately square root of the length of sample of solid dielectric and a constant coefficient describing the type of dielectric, method of conditioning, and the shape of applied potential.

Figure 5.17 and Appendix 3 show the obtained characteristics of flashover potential as a function of the length of sample at direct, alternating and surge 1.2/50 μs potentials

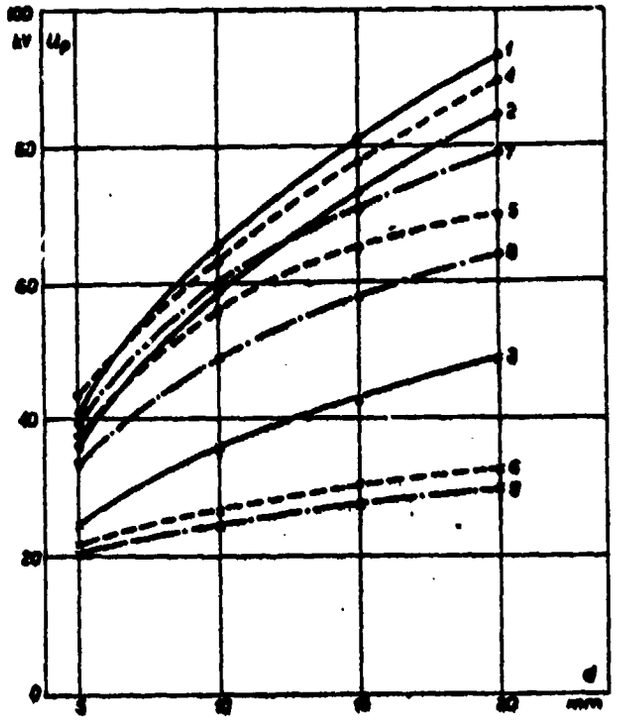

Figure 5.17. Flashover voltage as a function of the length of sample:
——— polymethylmethacrylate (1, 2, 3)
– – – – polytetrafluoroethylene (4, 5, 6)
–·–·–·– polyethylene (7, 8, 9)
Conditioning with direct potential. Flashover potential: direct potential (1, 4, 7); surge potential 1.2/50 μs (2, 5, 8); alternating potential (3, 6, 9)

for samples of polymethylmethacrylate, polytetrafluoroethylene and polyethylene. These samples were conditioned by means of direct potential.

The percentage increase of flashover voltage as a function of the length of sample for investigated materials is nearly the same. Polymethylmethacrylate is characterized by the highest surface strength in vacuum. The strength of polytetrafluoroethylene at direct and surge potentials is only slightly lower than the strength of polymethylmethacrylate. The flashover voltage of investigated samples at alternating potential is much lower than

the flashover voltage at direct and surge potentials. For polytetrafluoroethylene and polyethylene the flashover voltage is nearly the same and increases only slightly as a function of the length of sample.

For comparison of the strength of given solid dielectrics, we carried out also measurements of flashover voltage for samples conditioned with alternating potential (Figure 5.18 and Appendix 4). The obtained values of flashover potential for investigated dielectrics are higher than the corresponding flashover voltages for samples conditioned with direct potential.

Flashover voltages for samples of polytetrafluoroethylene and polyethylene conditioned with alternating potential showed little difference, similarly to the case of samples conditioned with direct potential, although the flashover voltage for samples of polytetrafluoroethylene is always higher than that of polyethylene. For investigated samples the flashover voltage at direct potential is much lower than the corresponding value of surge potential. The ratio of surge potential of flashover to direct potential of flashover is about 1.25 for all investigated samples.

We measured also the flashover potential for polytetrafluoroethylene and polyethylene at switching surges and after conditioning with direct potential. Experimental results and values of flashover voltage calculated according to the proposed equation are given in Appendices 5 and 6. Similarly to the case of polymethylmethacrylate, the surface strength of both dielectrics at switching surges also increased as a function of the length of sample.

Surface strength at various types of potentials (direct, surge 1.2/50 μs, alternating, switching surges) after conditioning with alternating potential is shown for polymethylmethacrylate in Appendix 7, for polytetrafluoroethylene in Appendix 8, and for polyethylene in Appendix 9. The same relations for investigated solid dielectrics as a function of the length of sample and the type of potential as after conditioning with direct potential

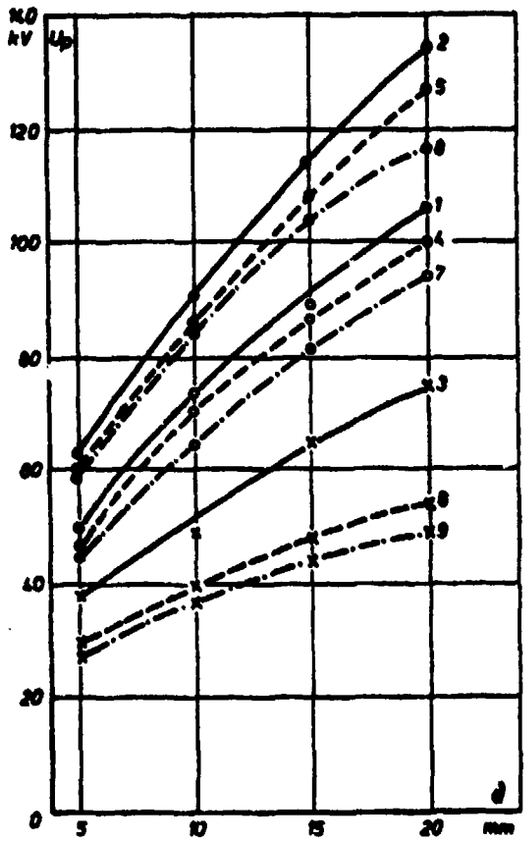

Figure 5.18. Flashover voltage as a function of the length of sample:
——— polymethylmethacrylate (1, 2, 3)
– – – – polytetrafluoroethylene (4, 5, 6)
—·—·—·— polyethylene (7, 8, 9)
Conditioning with alternating potential. Flashover potential: direct potential (1, 4, 7); surge potential 1.2/50 μs (2, 5, 8); alternating potential (3, 6, 9)

were observed. For all types of potentials the surface strength after conditioning with alternating potential is higher than after conditioning with direct potential.

5.5. EFFECT OF THE TIME OF DURATION OF SWITCHING SURGE WAVE FRONT ON VALUE OF FLASHOVER POTENTIAL

In order to make evaluation of the effect of shape of switching surge on the value of flashover potential, we performed experiments with polymethylmethacrylate at switching surges with various times of duration of the wave front and of the peak of surge. Results of mesurements are presented in Figure 5.19 and in Appendix 2.

For the sake of comparison we have given also values of flashover potential for direct, alternating and surge potentials. As the graph shows, surface strength at surge potential is higher than the strength at switching surges.

For analysis of the effect of the time of duration of switching surge wave front, the data from Figure 5.19 are plotted in Figure 5.20 as a function of the time of duration of wave front. At switching surges the flashover voltage decreases as the time of duration of the wave front increases. The minimum strength for a sample with length of 5mm and 10 mm occurs for potential with time of duration of switching wave front 80 μs. For waves with longer time of duration the flashover voltage increased somewhat. As the length of investigated sample is made longer, the minimum value of flashover potential is shifted in the direction of longer times of duration of the wave front, and for samples 15 mm and 20 mm long the minimum flashover voltage occurs for switching surge 150/1800 μs. The percent lowering of the value of flashover voltage with the time of duration of wave front is the largest for the longest samples.

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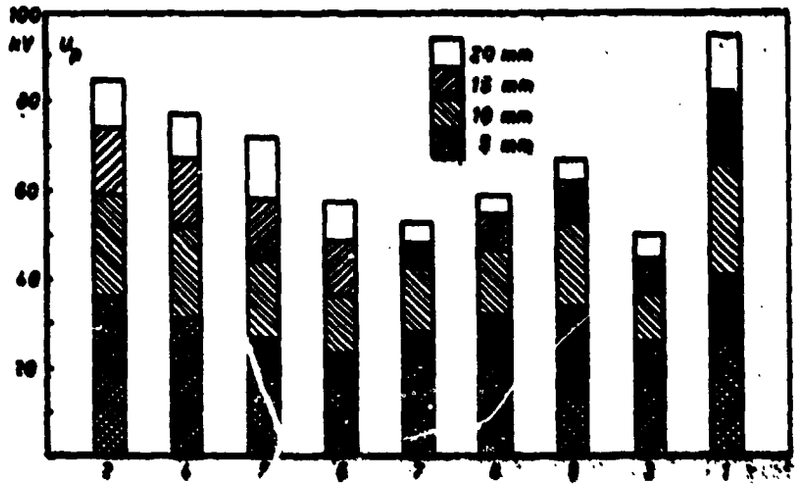

Figure 5.19. Effect of the shape of potential on value of flashover voltage. Sample from polymethylmethacrylate, conditioned with direct potential:

1 - direct potential
2 - normal surge 1.2/50 μs
3 - alternating potential 60 Hz
4 - switching surge 35/80 μs
5 - switching surge 50/250 μs
6 - switching surge 80/700 μs
7 - switching surge 150/1800 μs
8 - switching surge 400/2000 μs
9 - switching surge 600/3000 μs

Flashover potential as a function of the time of duration of surge wave front, with lines marking its maximum and minimum values, is shown in Figure 5.21.

The effect of the time of duration of switching surge wave front on surface strength was also examined for samples of polytetrafluoroethylene (Figure 5.22) and polyethylene (Figure 5.23). Character of changes is the same as for samples of polymethylmethacrylate. The appearance was noted of the characteristic minimum of strength at the time of duration of switching surge wave front 80 μs for samples 5 mm long, and at 150 μs for samples of the length 20 mm. For all the samples one observes a shift of the minimum of strength as a function of the time of duration

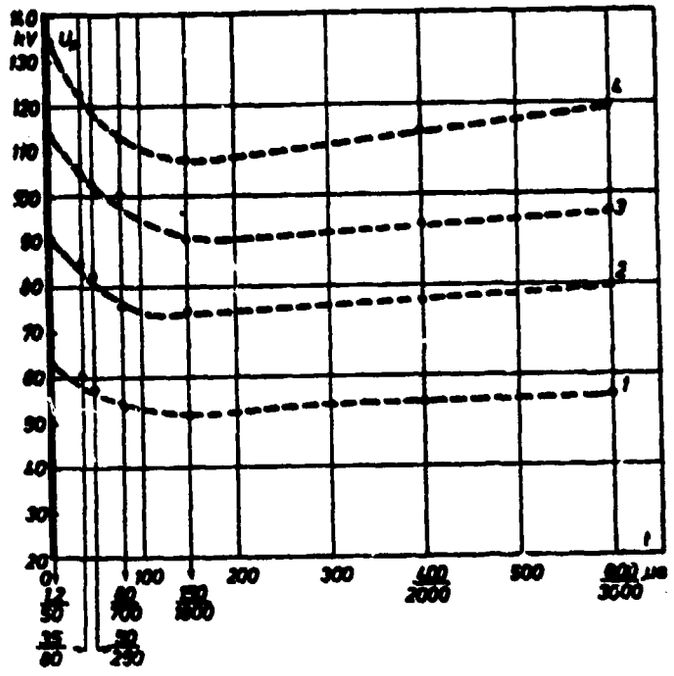

Figure 5.20. Flashover voltage as a function of the time of duration of switching surge wave front. Sample from polymethylmethacrylate. Conditioning with direct potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

of the surge wave front towards longer times as the length of sample increases.

In the opinion of the author, change of flashover voltage as a function of the time of duration of switching surge wave front is caused by surface charge which accumulates on the surface of solid dielectric. As the time of duration of the wave front increases the charge accumulating on surface of solid dielectrics becomes larger and larger. The appearance of charge on surface of solid dielectric is the result of the secondary emission of electrons,

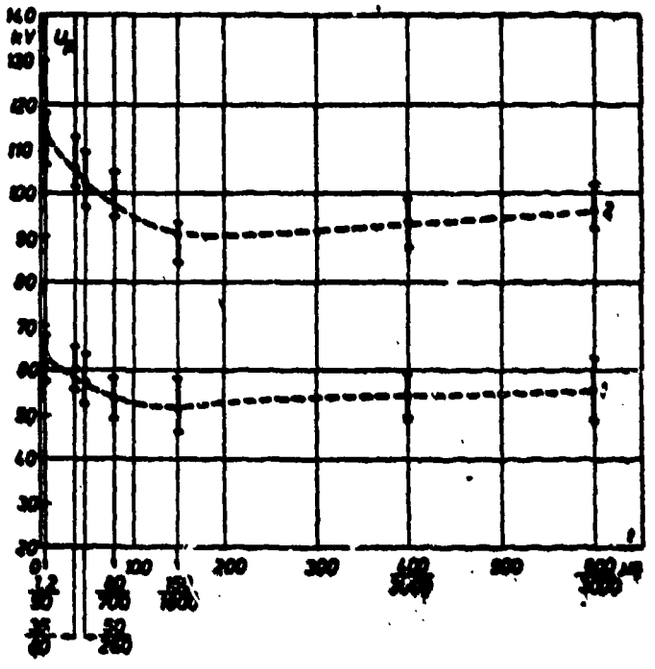

Figure 5.21. Flashover voltage as a function of the time of duration of switching surge wave front, showing the maximum and minimum values. Sample from polymethylmethacrylate, conditioning with direct potential.
1 - length 5 mm, 2 - length 15 mm

and the density of charge on surface is dependent on value of the coefficient of secondary emission δ as a function of the energy of primary electrons E_p, or function of the value of potential. Concurrently with increase of the time of duration of the surge wave front, there grows the amount of gas evolved from the surface of solid dielectric, which forms a thin sheath around the solid dielectric. Electrical discharges develop in this gas layer. Increase of thickness of the gas layer

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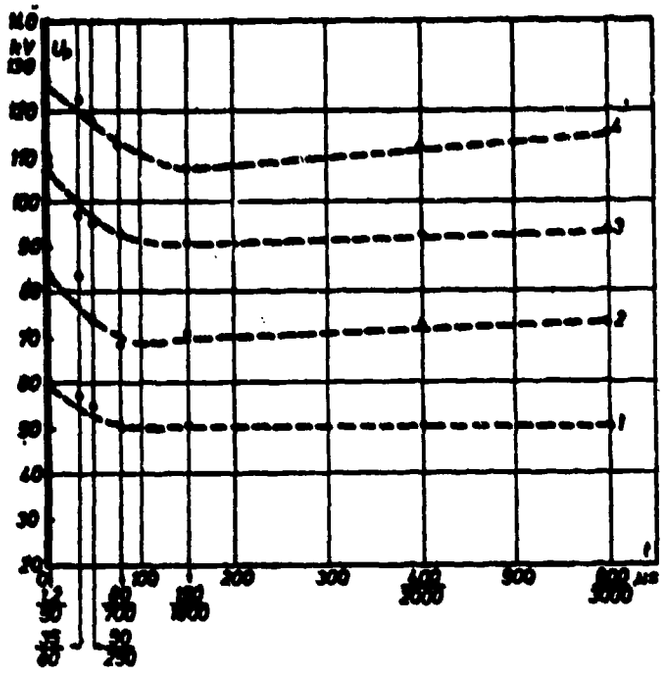

Figure 5.22. Flashover voltage as a function of the time of duration of switching surge wave front. Sample from polytetrafluoroethylene. Conditioning with direct potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

facilitates the development of discharging, and thus lowers the flashover voltage. But also the formation of a gas layer enables the transfer of a part of surface charge to this gas layer, and in this way the density of surface charge decreases. Moreover, the layer of gas around the surface of solid dielectric decreases its surface resistance, which also facilitates the flowing off of a part of surface charge. These two factors cause, in turn, an increase of surface strength as a function of the time of duration of switching surge wave front.

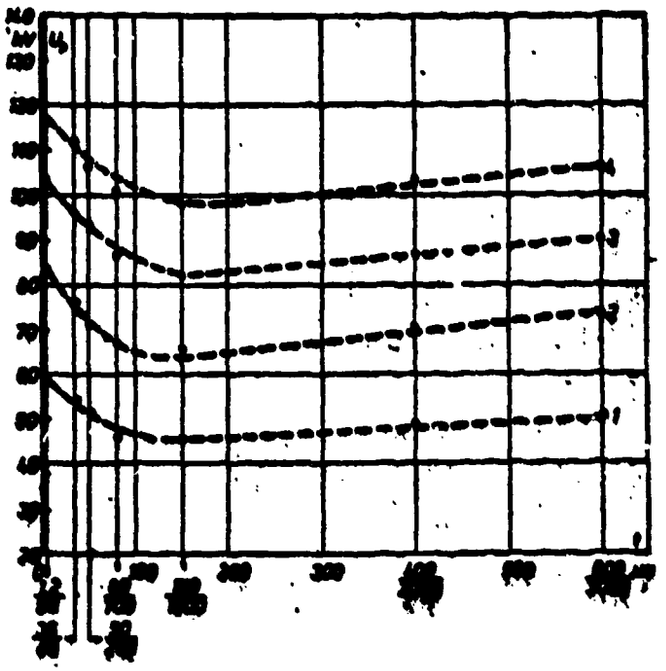

Figure 5.23. Flashover voltage as a function of the time of duration of switching surge wave front. Polyethylene sample. Conditioning with direct potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

The above mechanism of flashover at switching surges explains the observed fact that at first there is a lowering of flashover voltage and then there is rise of surface strength as a function of the time of duration of the switching surge wave front. A shift of the minimum of flashover voltage in the direction of longer times of duration of wave front confirms the above explanation of discharge mechanism. For longer samples, longer time is necessary to form a gas layer of suitable thickness, and for part of the surface charge to drain from larger surface of solid dielectric.

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It explains the observed fact that the surface strength as a function of the time of duration of switching surge wave front increases when the time of duration of wave front is larger than the time at which the minimum occurs for given length of sample.

A further confirmation of the proposed mechanism of the development of discharge for investigated materials is provided by analytical relation (5.2) developed by the author. This relation for flashover potential along the surface of solid dielectric in vacuum as a function of the time of duration of the surge wave front is as follows:

$$U_p = \begin{cases} \alpha_1 \beta^{\alpha_2} e^{-\tau_1 t} & \text{for } t \leq \varphi \\ \alpha_1 d^{\alpha_2} \left[e^{-\tau_1 t} + \left(1 - e^{-\tau_2 (t-\varphi)}\right) \right] & \text{for } t > \varphi \end{cases} \qquad (5.2)$$

where: α_1, α_2 - coefficients characterizing the type of solid dielectric and the method of conditioning,

d - length of sample,

d^{α_2} - effect of the length of sample,

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$e^{-\tau_1 t}$ - a factor causing the lowering of strength as a function of the time of duration of surge wave front, connected with charging of surface of dielectric

$1 - e^{-\tau_2 (t-\varphi)}$ - a factor causing increase of strength, connected with surface conductance of solid dielectric and with rate of draining of the charge,

τ_1, τ_2 - constants connected with type of material, length of sample, conditioning factors,

φ - time of accumulation of surface charge, above which there is the effect of the rise of surface strength connected with rise of surface conductance of solid dielectric,

t - time of duration of the surge wave front.

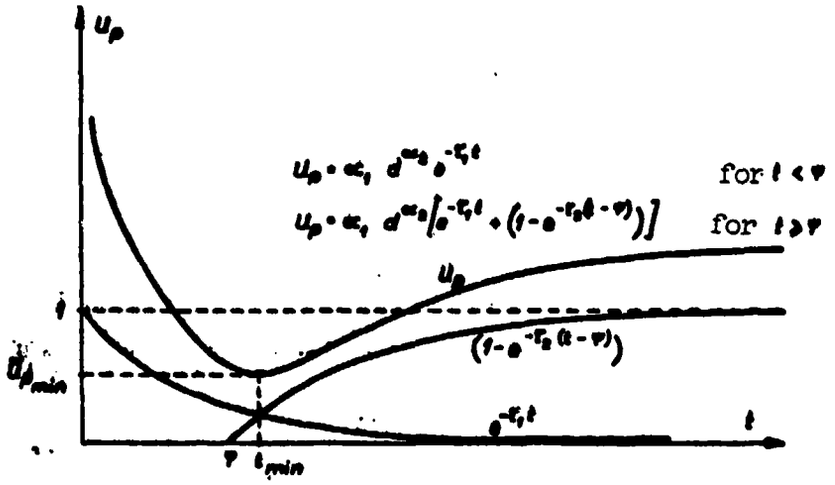

Figure 5.24. Flashover potential as a function of the time of duration of switching surge wave front.

$e^{-\tau_1 t}$ - effect of the accumulation of charge on surface of solid dielectric,

$1 - e^{-\tau_2(t-\psi)}$ - effect of surface conductance of solid dielectric on draining of charge,

ψ - time after which the draining of charge from surface of solid dielectric begins.

Figure 5.24 is a graphical interpretation of the relation (5.2). In order to obtain $U_{p\,min}$ or t_{min} it is necessary to calculate the derivative of function U_p with respect to t, since the remaining factors in the equation, i.e., α_1, α_2, are constants for a given type of dielectric and method of conditioning, and τ_1, τ_2, ψ depend on the length of sample d. Hence for a given sample, τ_1, τ_2, ψ, d are also constants.

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$\tau_1 = f_1(d)$ type of dielectric, conditioning,

$\tau_2 = f_2(d)$ type of dielectric, conditioning,

$\psi = f_3(d)$ type of dielectric, conditioning.

Hence the general equation appears as follows:

$$U_p = a_1 d^{a_2}\left[e^{-\tau_1(d)t} + \left(1 - e^{-\tau_2(d)(t - t_{(d)})}\right)\right] \text{ for } t \geq t_{(d)} \qquad (5.3)$$

For a given "d" and $t \geq t_{(d)}$, the derivative after transformation is expressed by equation:

$$\frac{dU_p}{dt} = a_1 d^{a_2}\left[-\tau_1 e^{-\tau_1 t} + \tau_2 e^{-\tau_2(t-t_{(d)})}\right]. \qquad (5.4)$$

The condition for extremes $dU_p/dt = 0$

$$a_1 d^{a_2}\left[-\tau_1 e^{-\tau_1 t} + \tau_2 e^{-\tau_2(t-t_{(d)})}\right] = 0. \qquad (5.5)$$

From which after transformation one obtains equation for t_{min}:

$$t_{min} = \frac{\tau_2 t_{(d)} + \ln \frac{\tau_1}{\tau_2}}{\tau_1 - \tau_2}. \qquad (5.6)$$

After substituting t_{min} into Equation (5.3) one obtains the relation for $U_{p\ min}$.

Tables 5.1 and 5.2 give values of flashover potential obtained experimentally and calculated according to Equation (5.2).

Investigation was also made of surface strength for three studied solid dielectrics on samples conditioned with alternating potential. The obtained results of surface strength are shown in Figures 5.25, 5.26 and 5.27. As follows from Figures and Tables, character of the surface strength for given solid dielectrics as a function of the time of duration of switching surge wave front after conditioning with alternating potential is the same as after conditioning with direct potential. As given in Section 5.3, the type of conditioning potential affects the state of surface of solid dielectric which, in turn, affects the coefficient of secondary emission.

Table 5.1. Flashover potential obtained experimentally and potential calculated for various times of duration of the switching surge wave front for polymethylmethacrylate, polytetrafluoroethylene and polyethylene. Conditioning with direct potential.

1 Rodzaj dielektryka	2 Długość próbki w mm	3 Zmierzone napięcie w kV						
		4 Czas trwania czoła udaru w µs						
		1,2	35	50	80	150	400	600
8 polimetakrylan metylu	5	36,2	31,3	26,6	22,4	27,3	31,3	32,8
	10	60,5	50,8	43,0	35,9	41,0	46,1	50,8
	15	73,3	66,4	57,0	48,4	46,9	54,7	60,9
	20	84,3	77,3	71,9	57,0	51,6	58,6	65,6
9 politetrafluoroetylen	5	37,6	27,3	23,4	21,9	26,3	25,8	27,3
	10	55,7	43,8	37,5	32,0	32,0	35,2	36,7
	15	65,2	57,8	50,0	44,5	43,2	49,2	51,6
	20	70,0	64,8	60,2	51,6	46,9	54,7	58,6
10 polietylen	5	33,8	25,0	22,7	19,5	20,0	24,2	27,3
	10	48,6	40,6	33,6	26,6	28,9	30,4	35,4
	15	57,6	50,0	46,9	36,7	37,5	42,2	43,8
	20	63,8	57,8	53,1	47,7	44,5	48,4	53,9

Table 5.1 Cont'd.

5 Коэффициенты уравнения (5.2)					6 Обозначения амплитуд в кВ						
					7 Длительность волны грозового импульса в мкс						
a_1	a_2	φ	τ_1	τ_2	1,2	30	50	80	150	400	600
12,987	0,638	78,46	0,00409	0,00338	38,0	31,3	29,4	26,3	27,3	30,8	32,8
12,987	0,638	89,00	0,00328	0,00288	56,1	46,6	43,0	38,7	38,0	46,3	50,8
12,987	0,638	92,30	0,00279	0,00301	78,3	67,8	57,1	49,4	46,9	54,5	60,9
12,987	0,638	136,90	0,00388	0,00220	87,1	76,2	71,9	60,1	51,6	58,2	65,6
19,006	0,453	49,7	0,01050	0,00913	39,4	27,3	25,4	20,6	18,8	26,8	29,3
19,006	0,453	53,2	0,00595	0,00193	50,0	43,8	40,1	36,3	31,3	31,4	36,7
19,006	0,453	60,3	0,00517	0,00258	60,8	50,1	50,0	46,0	43,2	46,0	51,6
19,006	0,453	110,8	0,00409	0,00250	73,9	60,0	60,2	53,3	46,1	52,5	58,9
13,807	0,527	53,66	0,00899	0,00527	32,2	25,2	22,7	21,1	20,3	25,8	27,1
13,807	0,527	60,68	0,00575	0,00250	46,5	38,0	34,3	31,5	28,1	33,3	35,9
13,807	0,527	98,70	0,00407	0,00224	57,5	49,9	46,9	41,5	37,5	43,5	48,8
13,807	0,527	101,00	0,00423	0,00260	66,9	57,7	54,1	47,7	43,5	48,5	53,9

Key: (1) Type of dielectric; (2) Length of sample in mm; (3) Measured potential in kV; (4) Time of duration of the surge wave front, in us; (5) Coefficients for equation (5.2); (6) Calculated potential in kV; (7) Time of duration of the surge wave front, in us; (8) Polymethylmethacrylate; (9) Polytetrafluoroethylene; (10) Polyethylene.

Table 5.2. Flashover potential obtained experimentally and potential calculated for various times of duration of the switching surge wave front for polymethylmethacrylate, polytetrafluoroethylene and polyethylene. Conditioning with alternating potential.

1 Rodzaj dielektryku	2 Długość próbki w mm	3 Powierzone napięcie w kV 4 Czas trwania czoła wiązki w μs						
		1,2	35	90	80	150	400	600
polimetakrylan metylu 8	5	62,4	60,0	57,2	53,3	51,7	54,1	55,6
	10	90,5	85,3	82,2	75,9	74,4	76,7	79,0
	15	113,0	105,0	103,6	100,4	90,8	93,1	96,3
	20	134,0	122,2	120,0	112,3	108,0	114,0	119,2
politetrafluoroetylen 9	5	50,0	57,2	54,8	50,2	50,7	50,2	50,9
	10	84,3	85,8	73,6	68,1	71,3	72,8	73,4
	15	108,0	97,0	95,5	93,7	91,6	92,6	93,3
	20	127,0	122,4	118,0	112,0	107,0	112,0	115,3
polietylen 10	5	58,6	54,8	51,7	46,3	46,3	49,4	50,9
	10	84,3	76,0	71,3	67,3	66,6	70,5	73,6
	15	104,0	95,5	93,1	86,9	82,2	86,1	90,2
	20	116,4	112,4	106,5	101,7	97,8	104,1	106,0

Table 5.2. Cont'd.

5 [illegible] (5.2)					6 [illegible] kV						
					7 [illegible] μs						
α_1	α_2	Φ	τ_1	τ_2	1,2	35	50	80	150	400	600
26,150	0,533	97,9	0,00149	0,00136	61,7	58,4	57,3	54,7	53,5	54,7	55,6
26,150	0,533	114,0	0,00165	0,00148	89,3	87,9	82,7	77,6	74,3	77,2	[illegible]
26,150	0,533	121,0	0,00168	0,00146	110,9	108,6	102,0	97,1	[illegible]	93,7	[illegible]
26,150	0,533	125,9	0,00149	0,00151	129,3	122,7	[illegible]	114,7	[illegible]	115,0	[illegible]
23,380	0,559	48,9	0,00205	0,00163	57,5	53,5	52,0	51,6	[illegible]	50,4	50,3
23,380	0,559	51,5	0,00281	0,00209	80,7	76,8	74,6	72,5	71,3	71,3	73,4
23,380	0,559	62,4	0,00211	0,00164	106,2	98,6	95,6	[illegible]	91,6	91,9	92,3
23,380	0,559	138,6	0,00113	0,00116	124,8	119,9	117,9	114,0	106,7	112,0	115,1
27,143	0,489	86,6	0,00297	0,00222	59,7	53,8	51,5	47,1	46,1	48,2	50,7
27,143	0,489	114,9	0,00279	0,00242	83,8	76,0	72,9	67,0	62,1	69,2	[illegible]
27,143	0,489	121,5	0,00184	0,00167	102,1	95,7	95,1	88,9	82,2	86,9	[illegible]
27,143	0,489	133,6	0,00140	0,00136	117,6	111,9	109,6	105,0	97,8	102,9	[illegible]

Keys same as table 5.1.

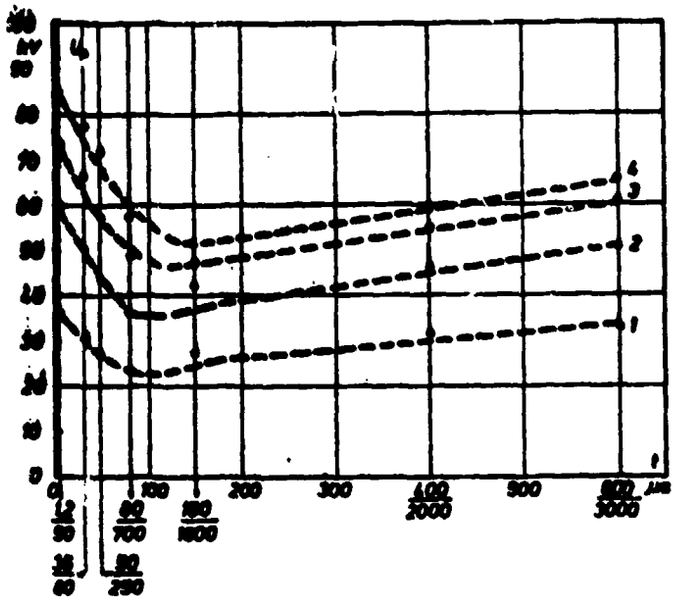

Figure 5.25. Flashover potential as a function of the time of duration of switching surge wave front. Polymethylmethacrylate sample, conditioned with alternating potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

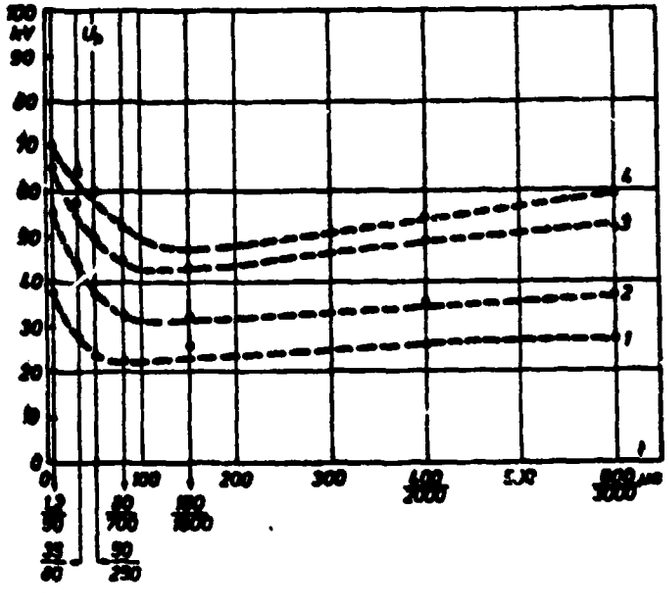

Figure 5.26. Flashover potential as a function of the time of duration of switching surge wave front. Polytetrafluoroethylene sample, conditioned with alternating potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

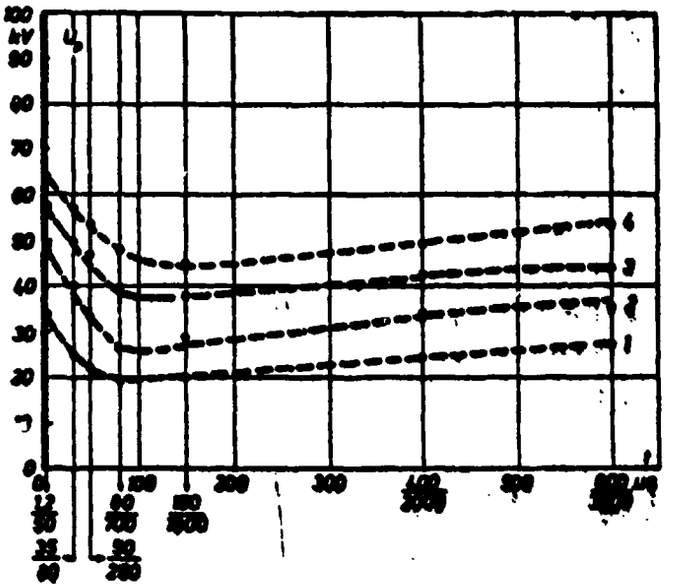

Figure 5.27. Flashover potential as a function of the time of duration of switching surge wave front. Sample from polyethylene, conditioned with alternating potential. 1 - length 5 mm, 2 - length 10 mm, 3 - length 15 mm, 4 - length 20 mm

The effect of the time of duration of the ridge (peak) of switching surge on flashover potential was not systematically investigated, since flashovers usually appeared at the peak of surge or near it. Only in a few cases we observed that flashover occurred on the ridge (slope), a few microseconds behind the peak of the surge.

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6. DEGRADATION OF SURFACE OF SOLID DIELECTRIC CAUSED BY FLASHOVERS

Studies of surface strength of solid dielectrics in vacuum have shown that the flashover voltage as a function of consecutive flashovers has no constant value. It was observed that after 25-30 flashovers, surfaces of the sample of solid dielectric suffered a strong damage, and the potential of flashover had smaller and smaller value (Figure 6.1). The degree of degradation of a given sample depends, in addition to the number of flashovers, also on such factors as the method of conditioning, type of applied potential, power of test source, and resistance connected in series with investigated object.

Studies of the degradation of surface of solid dielectrics caused by flashovers were conducted at direct potential. As a source of potential we used a test system 90 kV with power 1.3 kVA, and resistance of value 600 kΩ was included in the circuit of the source and sample of dielectric. The state of shorting of the system was interrupted after 10 ms.

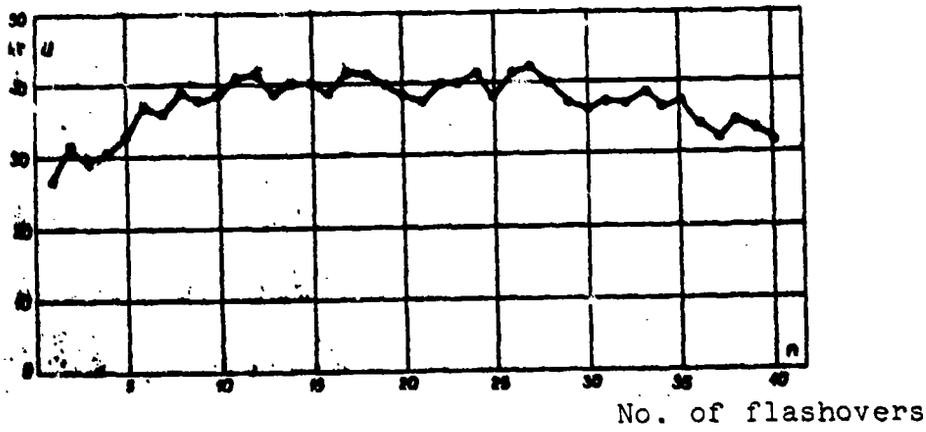

Figure 6.1. Flashover voltage as a function of consecutive flashovers. Direct potential, pressure 133.322×10^{-5} Pa (10^{-5} Tr), polymethylmethacrylate sample 5 mm long

The mechanism of degradation of solid dielectrics in vacuum is not yet fully known. In this work the data concern the degradation of three investigated solid dielectrics: polymethylmethacrylate, polytetrafluoroethylene and polyethylene. Our studies of surface degradation of solid dielectrics are carried out on the basis of analysis of the oscillograms of the course of switching surges, photographs of the surface of solid dielectrics magnified by means of an electron microscope, and measurements of infrared absorption spectra. 184

6.1. OSCILLOGRAMS OF SWITCHING SURGES CORRESPONDING TO CONSECUTIVE FLASHOVERS

From a large number of recorded oscillograms of switching surges corresponding to consecutive flashovers we chose a few characteristic ones for our analysis.

To determine the effect of consecutive flashovers on value of flashover voltage, we applied to the insulation system switching surges of constant value of potential sufficient to cause a flashover. Figure 6.2 shows oscillogram of consecutive switching surges 600/3000 μs of potential with value 28.0 kV. As the Figure shows, the first flashovers did not cause lowering of the value of flashover voltage. Moreover, not all surges with the same value of potential caused a flashover along the surface of solid the dielectric. 185

Figure 6.3 illustrates the case in which after the first flashover (which occurred for surge 2 at the given potential) there are two further flashovers; these flashovers are at lower value of surge. The surge 3 applied to sample caused only one flashover, which appeared at the peak (ridge) of surge.

In the majority of cases the degradation of the surface of solid dielectric does not occur violently (suddenly), but there happen to be cases where after a few flashovers the investigated

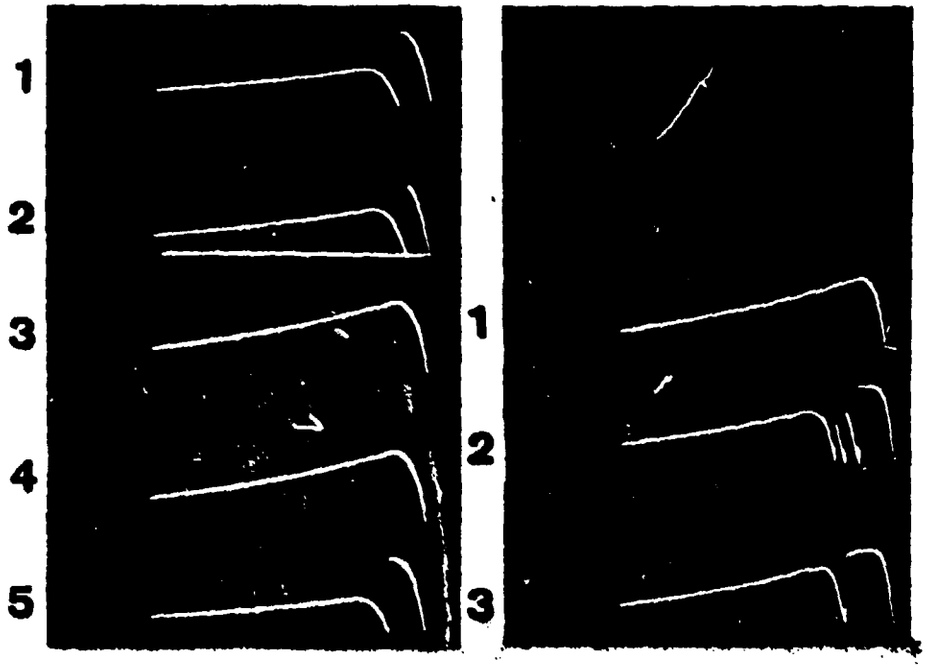

Figure 6.2 (left). Oscillogram of consecutive switching surges 600/3000 μs. Polymethylmethacrylate sample 5 mm long. Value of potential 28.0 kV. Surges from No. 1 to No. 5

Figure 6.3 (right). Oscillogram of consecutive switching surges 80/700 μs. Polymethylmethacrylate sample 5 mm long. Value of potential 21.5 kV. Surges from No. 1 to No. 3

sample becomes completely destroyed. Figure 6.4 shows oscillograms which evidence successive degradation of the surface of solid dielectric, caused by consecutive flashovers of switching surges 400/2000 μs. The damage to the surface of a solid dielectric is here very strong. The second surge caused the flashover at lower value of potential. The flashover occurred at the front of surge, and was followed by two further flashovers. At the third surge, the flashover occurred at even lower values of potential, and altogether

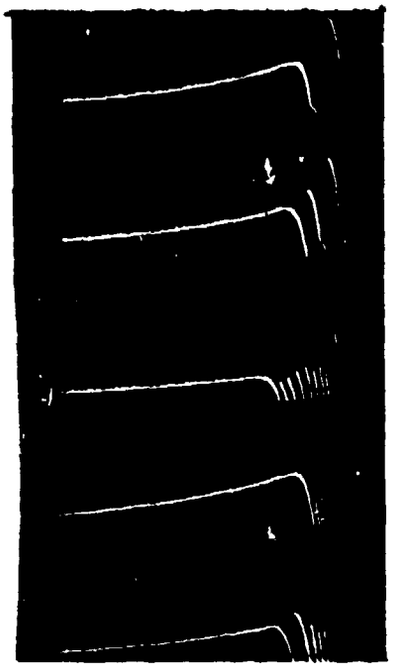

Figure 6.4. Oscillogram of consecutive switching surges 400/2000 μs. Polymethylmethacrylate sample 5 mm long. Value of potential 34.0 kV. Surges from No. 1 to No. 5

there were 9 ignitions. Switching surges cause relatively fast degradation of surfaces of solid dielectric. As a result, there are multiple flashovers during one switching surge often, leading to the formation of a conducting path on the surface of solid dielectrics. Not all samples (Figures 6.2 and 6.3) suffered such an extensive damage as is shown by oscillogram in Figure 6.4.

Figure 6.5 shows the case where the first flashover (which occurred only at the third wave of potential of given value) made such a strong damage to the sample that the next flashover formed already a completely conducting path.

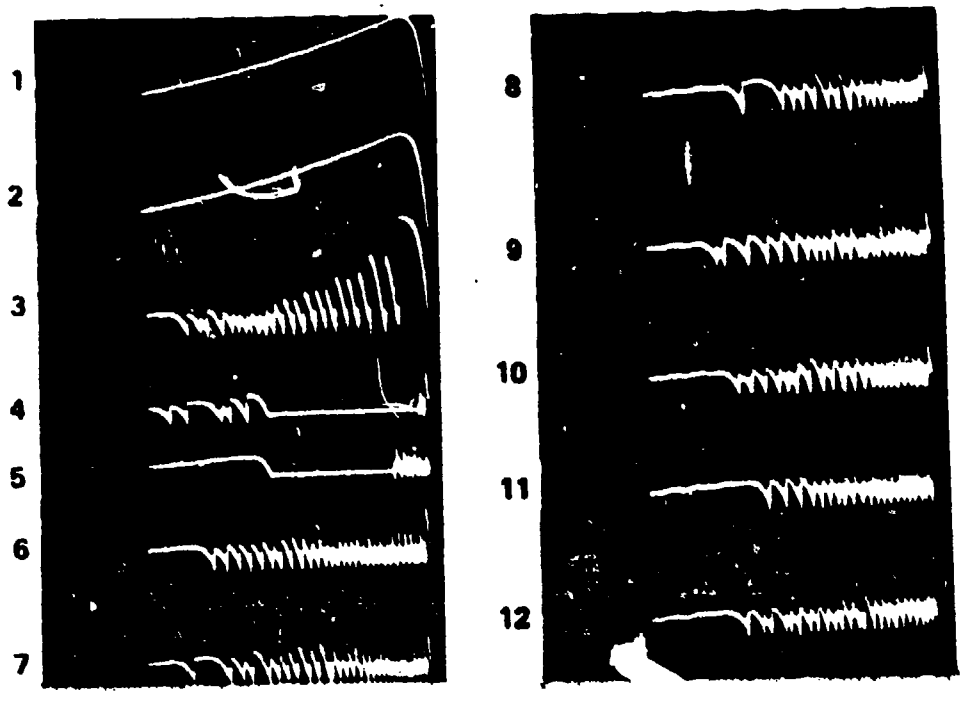

Figure 6.5. Oscillogram of consecutive switching surges 80/700 μs. Polymethylmethacrylate sample of length 5 mm. Value of potential 25.0 kV. Surges from 1 to 12

In the majority of cases the degradation was not so rapid as shown in Figures 6.4 and 6.5. In practice, only 25-30 flashovers caused severe degradation of the surface of solid dielectric and eliminated the sample from further studies.

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6.2. STUDY OF THE SURFACE OF SOLID DIELECTRIC BY MEANS OF ELECTRON MICROSCOPE

When studying the surface of samples by means of electron microscope it was observed that after the flashover there are canals (paths) of tree type on the surface of dielectrics, indicating a similarity between the mechanism of flashover in vacuum and flashover in air.

To illustrate character of discharges, photographs of canals obtained for three investigated materials are presented. The photographs are made for samples conditioned with direct potential, using also direct potential as test potential.

Figure 6.7 shows a sample from polymethylmethacrylate after 10 and 20 flashovers. On the picture showing the surface of dielectric after 10 flashovers there is only a streak indicating the start of discharging canal. But after 20 flashovers the canal is already very distinct and has numerous side branches, which are shown in Figure 6.8 in 300 X magnification. Inspection of the above photographs suggests that the surface of the canal is smooth. The canal arose as a result of high temperature of an electric arc, which caused melting and erosion of solid dielectric and its transfer onto the surface of electrodes.

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In order to examine closer the phenomenon of transfer of solid dielectric onto electrodes we used a sample having one edge notched (Figure 6.9). The location of the notched edge was changed, i.e., once it touched cathode, and then the notched edge touched anode. As is seen from pictures, particles of solid dielectric were placed on the electrode on circumference of samples. If the notched edge touched anode, then on the anode remained the trace of notch in the form of suitable placing of particles of solid dielectric. Distinctly shaped trace of notch evidences the transfer of particles of solid dielectric along the surface of dielectric and not in space near the dielectric.

Figure 6.6. Sample of polymethylmethacrylate before placing in vacuum chamber, without traces of surface discharging. Magnification 100 X.

We conducted also studies of the surface of polytetrafluoroethylene after 10 and 20 flashovers (Figures 6.11 and 6.12). The discharging canals which for polytetrafluoroethylene appeared after 10 flashovers are already very distinct (and not only a streak as for polymethylmethacrylate) and form a groove deep into polytetrafluoroethylene. One can observe also side branches, although they are not so strong.

A very interesting is the whole discharge canal after 20 flashovers at only 45 X magnification, shown in Figure 6.12. The canal starts at the cathode as a narrow and deep groove, gradually broadens and causes more and more small ridges. At a distance of about 1/3 of the length of sample from the anode there is branching, as a result of which the anode is reached by two branches. They are much broader and, moreover, one branch

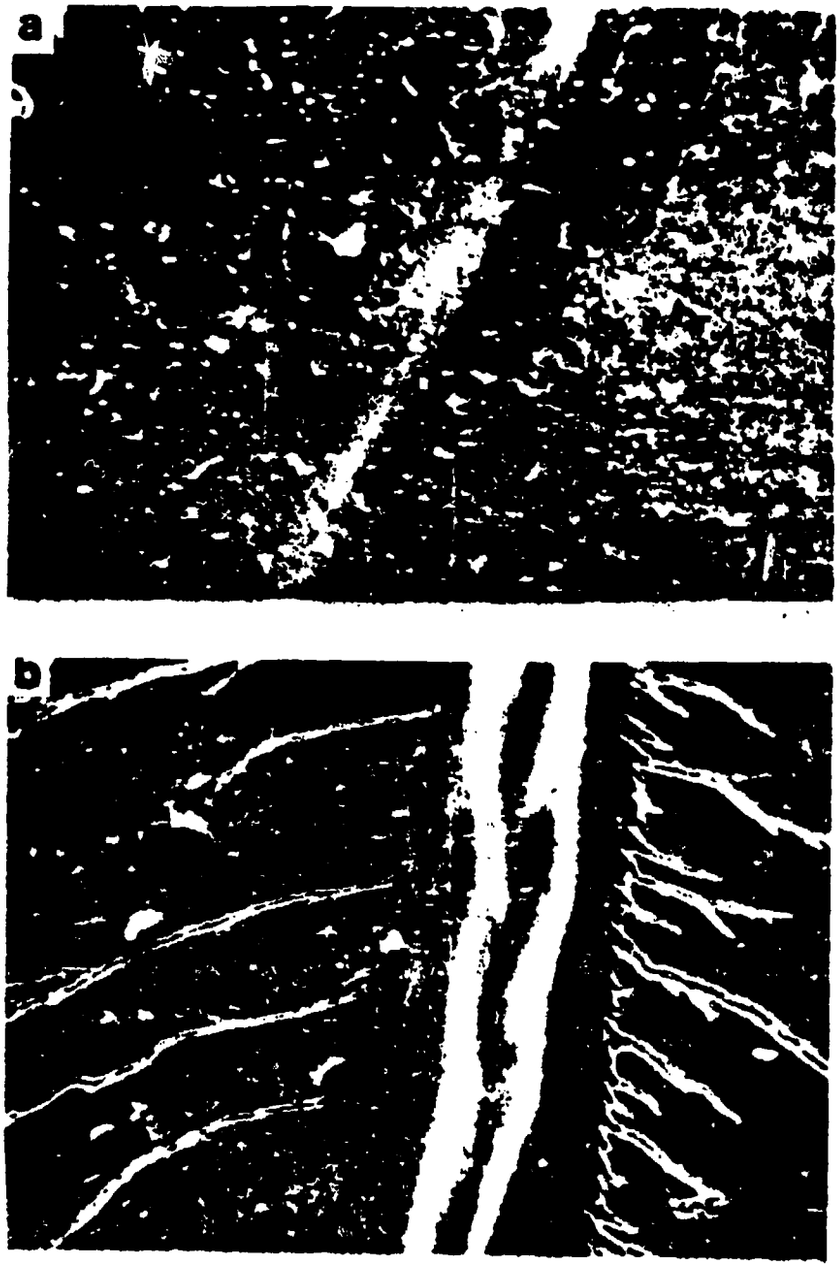

Figure 6.7. Sample of polymethylmethacrylate, magnification 100 X: a) after 10 flashovers, b) after 20 flashovers

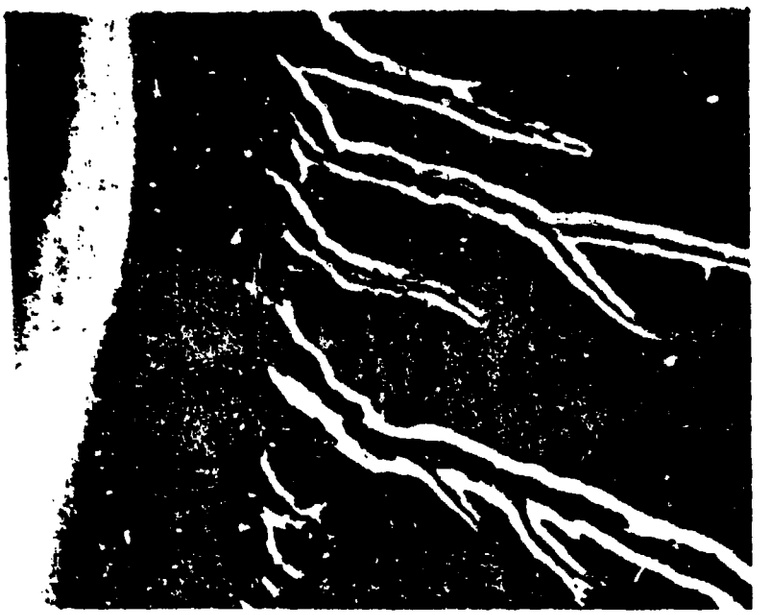

Figure 6.8. Sample of polymethylmethacrylate after 20 flashovers, magnification 300 X.

Figure 6.9. Sample of polymethylmethacrylate with one edge notched.

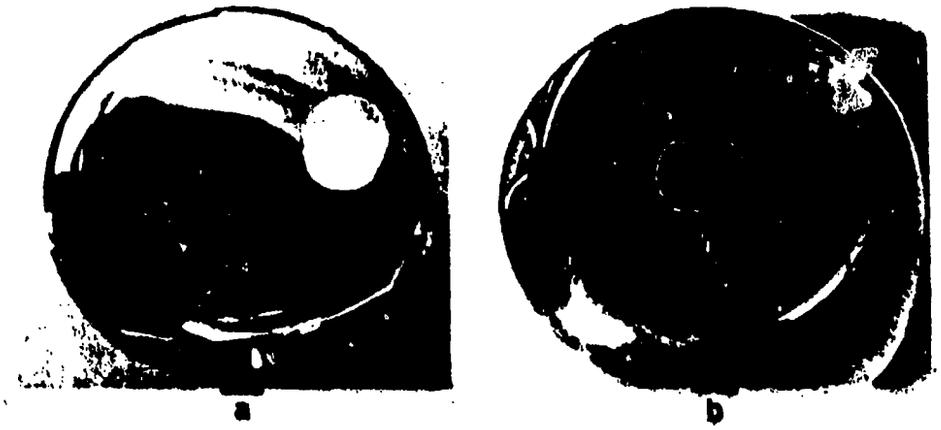

Figure 6.10. Anode with deposited particles of solid dielectric - polymethylmethacrylate - as a result of flashovers; a) notched edge touched cathode, b) notched edge touched anode

appears to be gradually disappearing. Such a character of discharge confirms that particles of solid dielectric are distributed uniformly along the edge of solid dielectric on anode (Figure 6.10).

Microscopic studies of the state of surfaces of solid dielectric after flashovers were also conducted for samples from polyethylene. It was found that surfaces of polyethylene suffers the strongest degradation. Distinct signs of discharge appeared on the surface of polyethylene already after 10 flashovers (Figure 6.13). In comparison with previous two dielectrics, they are deeper and are characterized by a broken line. The character of the broken line is visible even better on photographs taken after 20 flashovers (Figure 6.14). In addition, this broken line has variable width and depth along the path of discharge. The above photographs evidence a poorer uniformity of polyethylene in relation to polymethylmethacrylate and polytetrafluoroethylene.

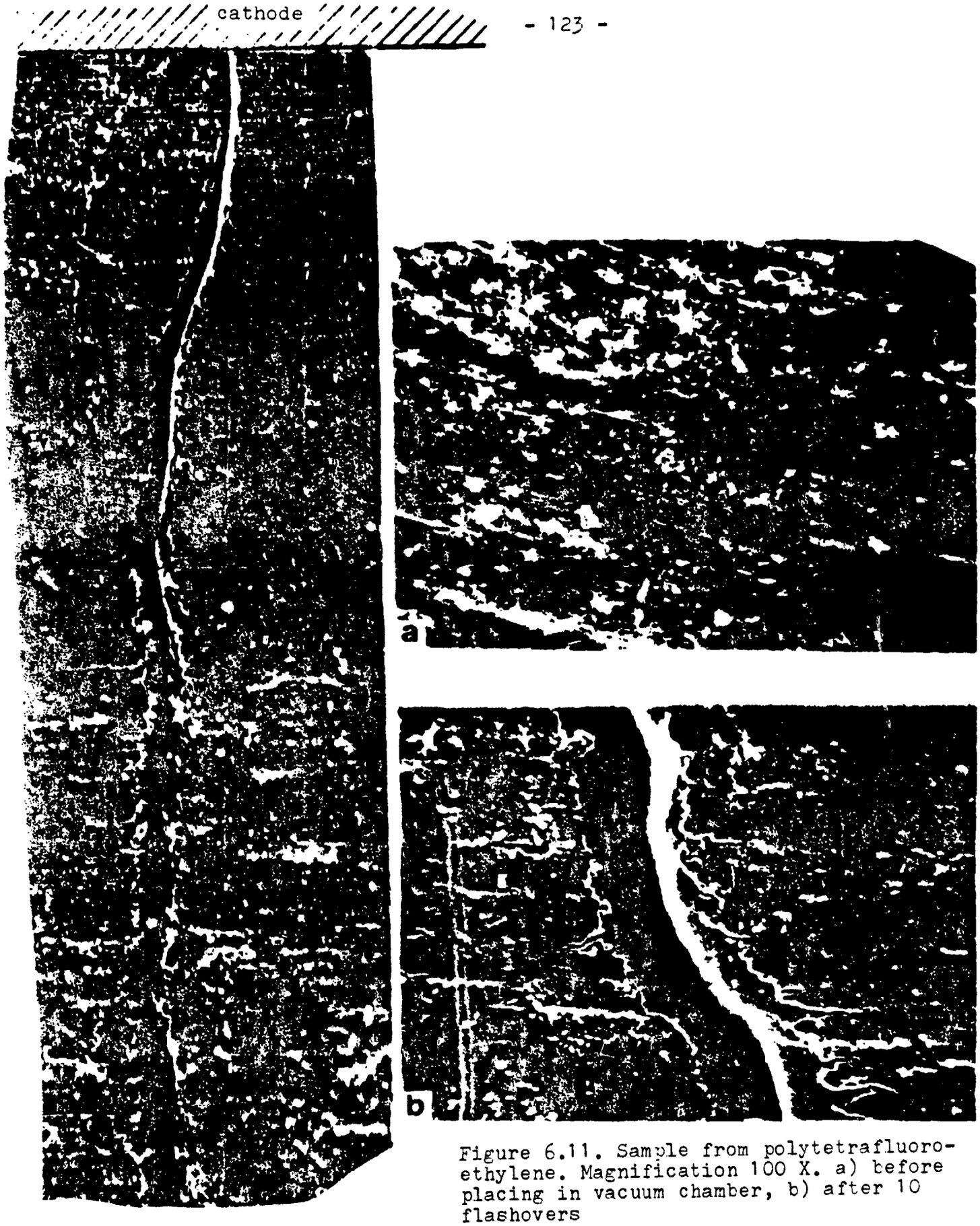

Figure 6.11. Sample from polytetrafluoroethylene. Magnification 100 X. a) before placing in vacuum chamber, b) after 10 flashovers

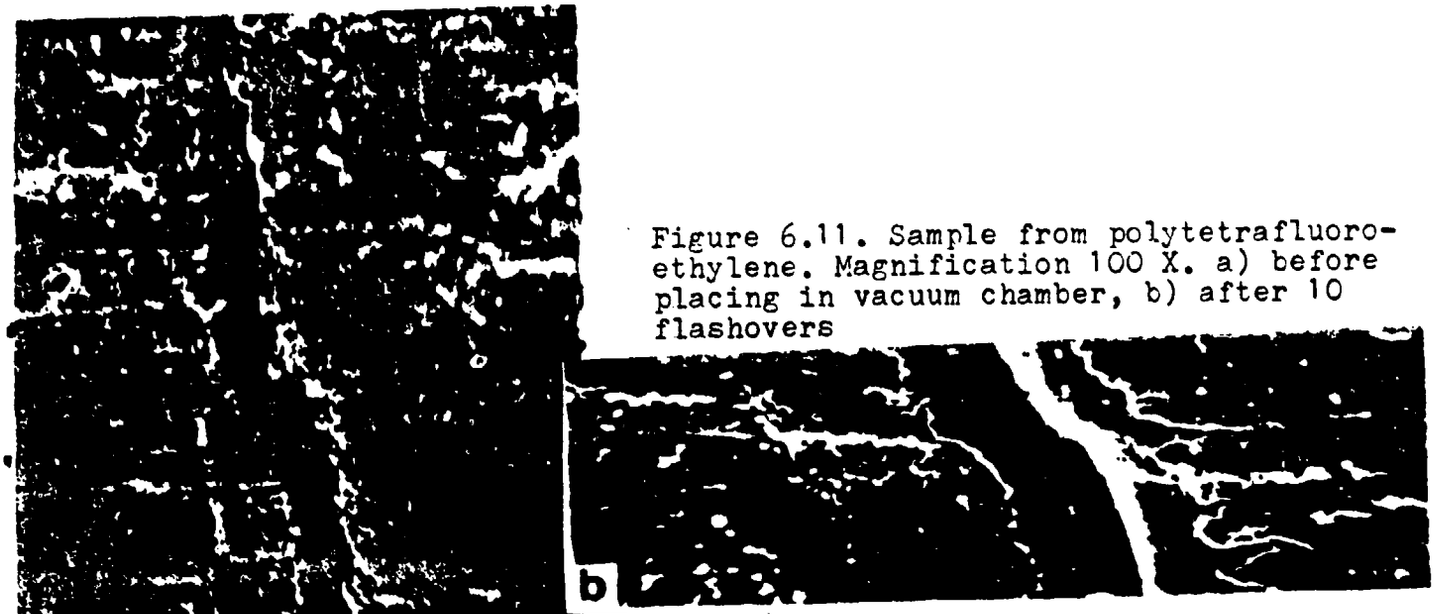

Figure 6.11. Sample from polytetrafluoroethylene. Magnification 100 X. a) before placing in vacuum chamber, b) after 10 flashovers

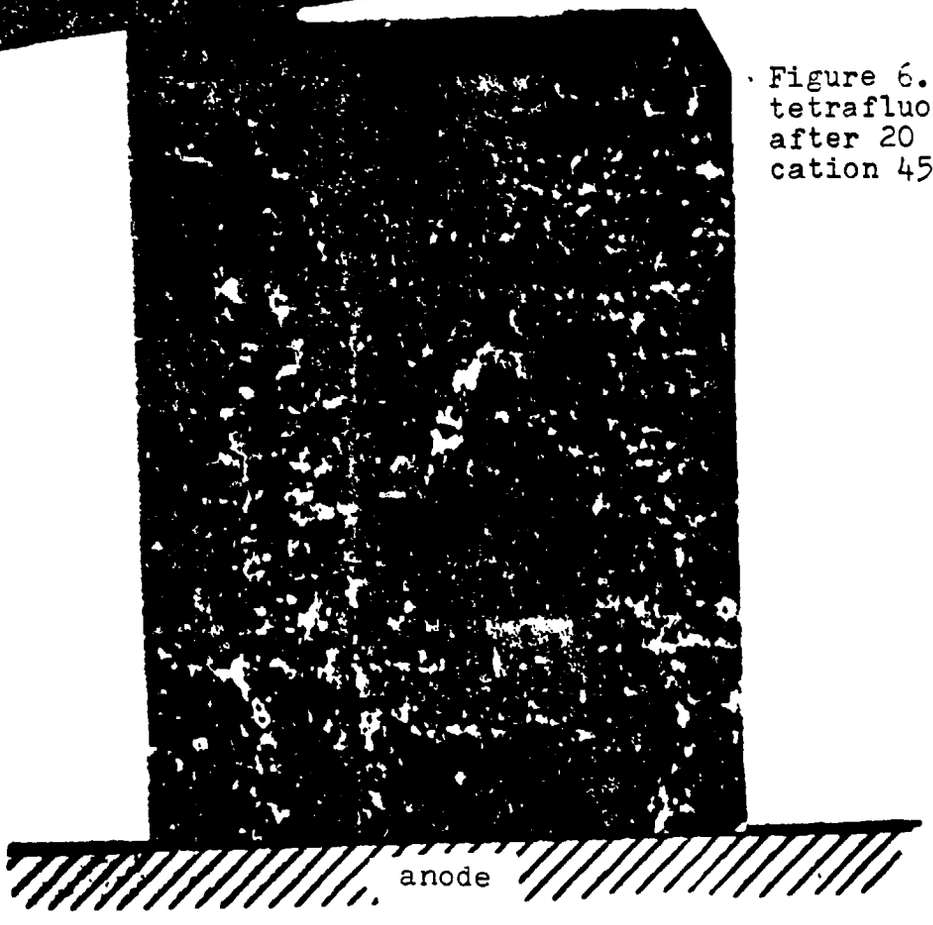

Figure 6.12. Sample from polytetrafluoroethylene 10 mm long, after 20 flashovers. Magnification 45 X

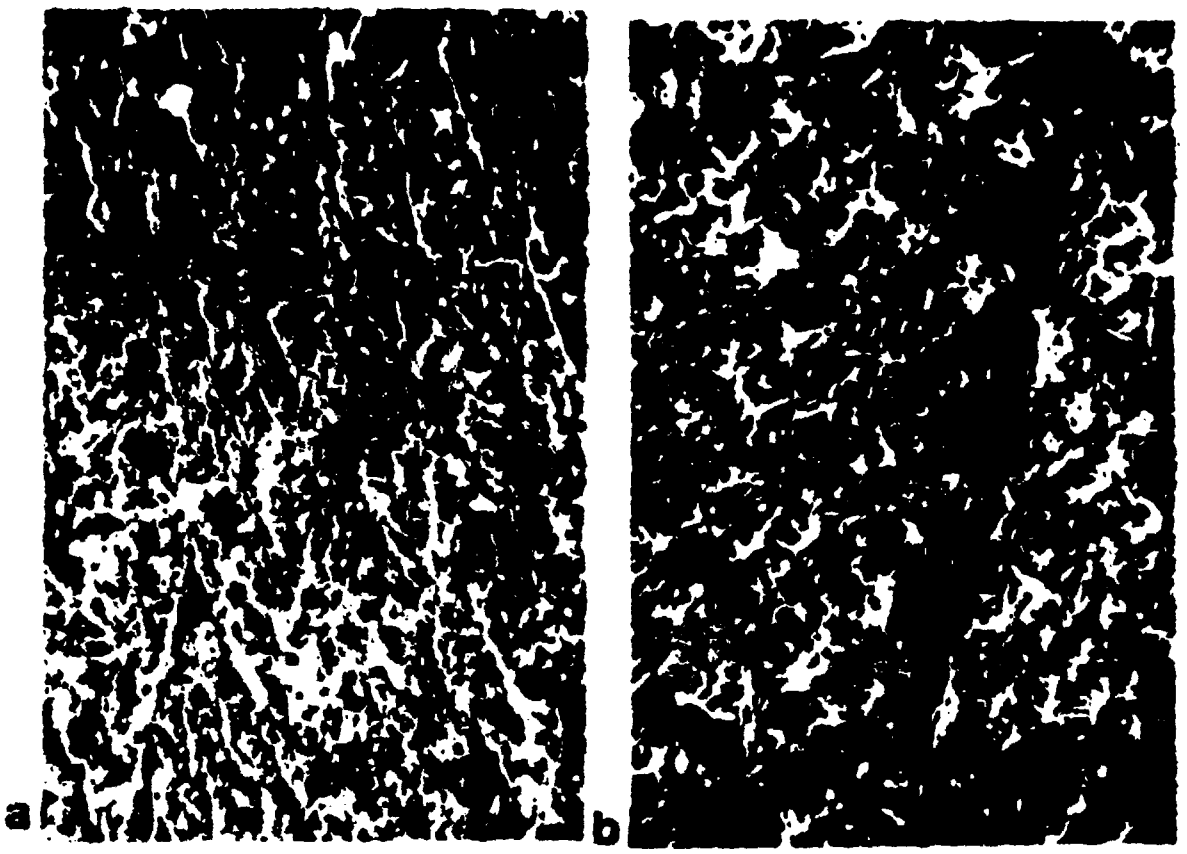

Fig. 6.13. Sample from polyethylene, magnification 100X; a) before placing in vacuum chamber, b) after 10 flashovers

Figure 6.14. Sample from polyethylene after 20 flashovers. Magnification 100 X

As is seen from the presented photographs of surfaces of solid dielectrics after flashovers, the strongest degradation of the surface of dielectric occurs for polyethylene, and the least for polymethylmethacrylate. It is also characteristic for polymethylmethacrylate that discharges cause the appearance of a broader and not so deep canal, which is the result of melting and erosion of the surface of polymethylmethacrylate. For polytetrafluoroethylene and polyethylene, flashovers lead to the formation of very distinct canals, which are considerably deeper and narrower than for polymethylmethacrylate.

6.3. SPECTROGRAPHIC STUDIES

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Samples for studies, in the form of thin films, were sliced by means of microtome directly from solid dielectric subjected to the action of flashovers as in Section 6.2.

It was noted that repeated flashovers polished the surface of solid dielectric to some degree. The canals of flashovers along the surface of solid dielectric were visible with the naked eye.

Infrared absorption spectra in the range 650-4600 cm^{-1} were obtained to follow changes occurring in the structure of investigated solid dielectrics under the action of flashovers. Samples examined included initial samples and samples after the action of 20 flashovers.

The infrared absorption spectra in their whole range failed to show any distinct changes in structure of the investigated solid dielectrics under the action of electric discharges in vacuum.

Only for polyethylene, which according to studies of discharge canals by means of electron microscope suffered the strongest damage to surface, certain changes occurred in absorption spectra of samples after 20 flashovers. 193

It may be assumed that possibly oxidation or destruction of given materials occurred to such a small degree that the resultant changes are outside of the sensitivity of spectrophotometer. The conditions of studies in vacuum, and small amounts of residual gas, would support this conclusion. Moreover, one has to remember a very short time of duration of discharges, and a small area of surface changes.

The usefulness of spectrographic studies for evaluation of the extent of degradation of the surfaces of solid dielectric as a result of flashovers in vacuum is very limited. This arises from the fact that degradation of the surface of samples is nonuniform and takes place in a very small area. Another disadvantage of this method is difficulty of preparing samples of the same thickness

and uniformly prepared surface in order to obtain the same transmission level of the spectrum of examined sample. This difficulty applied particularly to polymethylmethacrylate.

6.4. CONCLUSIONS FROM STUDIES OF DEGRADATION OF SURFACE OF SOLID DIELECTRIC

From the presented results of studies of degradation of samples it follows that thermoplastic materials in vacuum loose their insulating properties after a dozen or so of discharges. Hence studies of the potential of flashovers along the surface of solid dielectrics should be carried out at possibly the smallest current of shorting and the shortest time of shorting, to reduce the damage of surfaces of solid dielectric to a minimum. In spite of limiting the current flowing during the flashover along the solid dielectric, the degradation is still considerable and in practice samples undergo destruction after about 25-30 flashovers. Among the investigated materials, polyethylene suffers the strongest degradation, and polymethylmethacrylate is the least affected.

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7. SUPPLEMENTARY STUDIES OF THE MECHANISM OF FLASHOVER ALONG SURFACES OF SOLID DIELECTRIC IN VACUUM

Results of studies of the surface strength of thermoplastic dielectrics in vacuum are described in Chapter 5. Results of studies of degradation of the surfaces of solid dielectric caused by flashovers (Chapter 6) contain also some data and considerations concerning mechanism of the flashover along surfaces of solid dielectric in vacuum. This Chapter, in turn, will present results of further studies aiming at getting better knowledge of the mechanism of flashover along thermoplastic materials in vacuum.

A system for observation and recording of surface discharges (Figure 7.1) was used for studies of the mechanism of flashover along solid dielectric in vacuum at direct potential (d.c.) or alternating potential (a.c.). This system enables to record the course of discharge on magnetoscope tape, and then to reproduce the discharge and to choose a proper frame illustrating an interesting stage of discharge.

In investigations of the mechanism of flashover along surfaces of solid dielectric in vacuum at direct potential the author observed [53, 76] the occurrence of local flashes on the surface of solid dielectric before the flashover. He explained this pre-flashover discharge on a part of surface of solid dielectric as due to accumulation of surface charge. Various stages of surface discharge at direct potential were recorded by means of the system given in Figure 7.1, and were made permanent on photographs shown in Figure 7.2.

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Photograph No. 1 (Figure 7.2) shows the first unclear local pre-flashover discharge (glow), which appeared and disappeared irregularly at a constant value of potential. If the potential was slightly raised, the pre-flashover discharge was stronger and clearer, but it did not reach yet the full flashover stage.

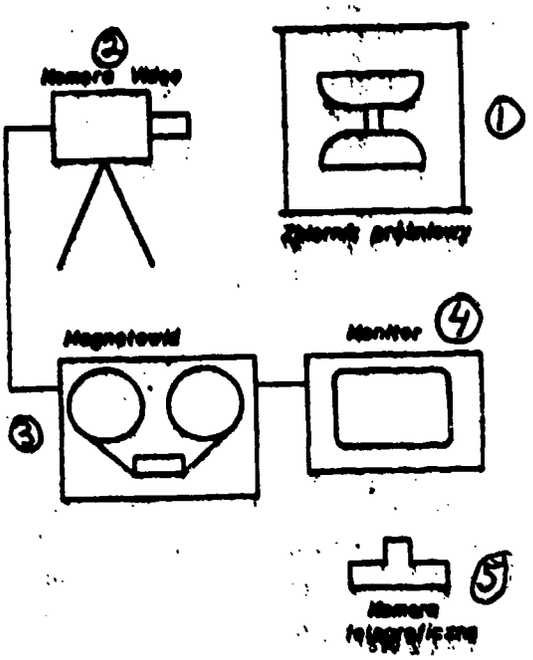

Figure 7.1. Diagram of a system for observation and recording of discharges on surface of solid dielectric.
1 - vacuum chamber, 2 - Video camera, 3 - magnetoscope, 4 - monitor, 5 - photographic camera

Photograph No. 2 (Figure 7.2) shows the state of pre-flashover discharge after raising the potential by 5 kV in the time of 6 seconds in relation to Photograph No. 1. We observe here a bright clear thread of glowing discharge, which moves on the surface of solid dielectric and fades. Photograph No. 3 shows the stage of pre-flashover discharge at constant value of potential after the time of 0.5 sec with respect to Photograph No. 2. The intensity of glowing discharge is very faint and this discharge nearly entirely fades away.

After the period of time of about 0.4 sec, counting in relation to Photograph No. 3, there was a flashover at unchanged value of potential (Photograph No. 4, Figure 7.2). Then, in

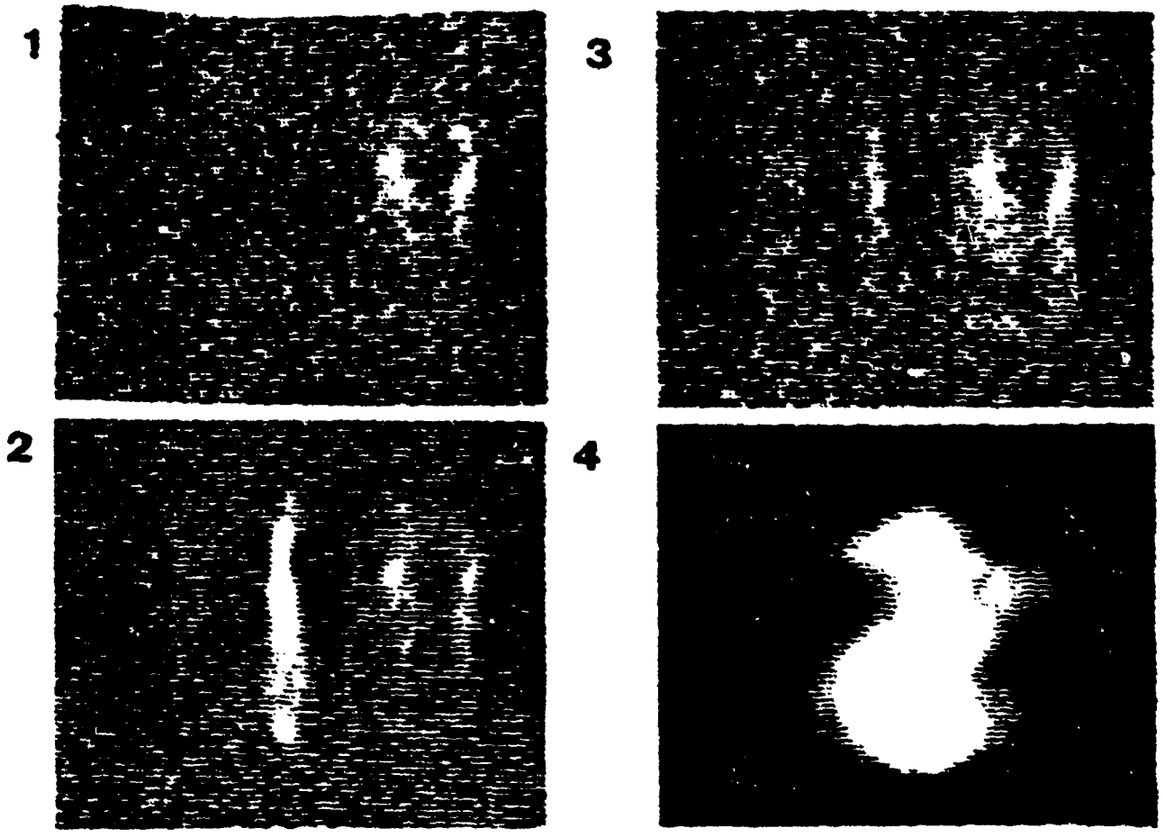

Fig. 7.2. Discharges on the surface of solid dielectric in vacuum.

intervals from 0.05 to 0.1 sec followed consecutive flashovers.

After a few flashovers at direct potential one could see on the surface of investigated samples the formation of a discharging canal, which after a dozen or so flashovers is already well formed. There is an intensive degradation of the surface of a solid dielectric along this canal.

Analysis of the dvelopment of flashover at alternating potential was carried out on the basis, among others, of microscope photographs of discharging canals on the surface of solid dielectric. The testing apparatus used enabled to determine at which sign of potential on ungrounded electrode the flashover took place. The first few flashovers appeared at different signs of potential at ungrounded electrode. In the majority of cases after ten-twenty discharges the flashovers appeared at the same polarity of ungrounded electrode. Usually the number of canals on surface of solid dielectric at alternating potential was larger than at direct potential and these canals were considerably more branched. Moreover, in addition to the main canal, at alternating potential one could observe a couple of semi-developed canals. Photographs in Figures from 7.3 to 7.6 give examples of discharge canals at alternating potential.

Figure 7.3 shows discharge canals which appeared after 40 flashovers at various places on the whole circumference of the sample of polymethylmethacrylate 5 mm long. Comparison of the discharge canals shows that the highest degradation was suffered by surface of dielectric in Figure 7.3b. The canal of this discharge is considered as the main canal in which the majority of flashovers took place.

Discharges develop on the outside of the sample, and the electric arc is the broadest in its middle part, which is evidenced by the width of the damaged belt of solid dielectric in 7.3b. An interesting fact is the appearance of branching (Figure 7.3b) and a broader canal at one of the electrodes. Figure 7.3a shows

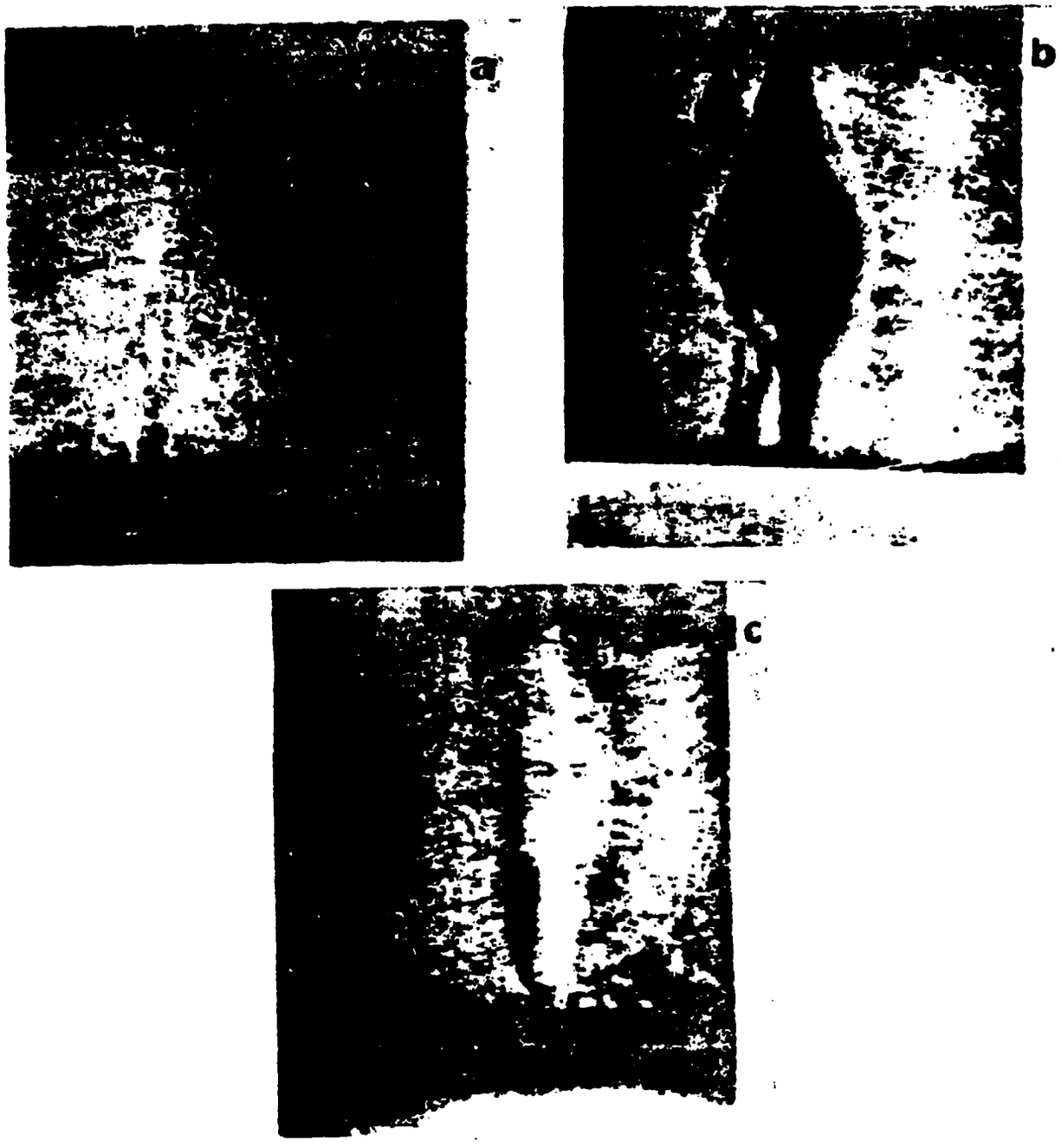

Figure 7.3. Sample of polymethylmethacrylate 5 mm long after 40 flashovers. Magnification 13 X. Alternating potential, value of potential 42 kV.
a) side canal 1, b) the main canal, c) side canal 2

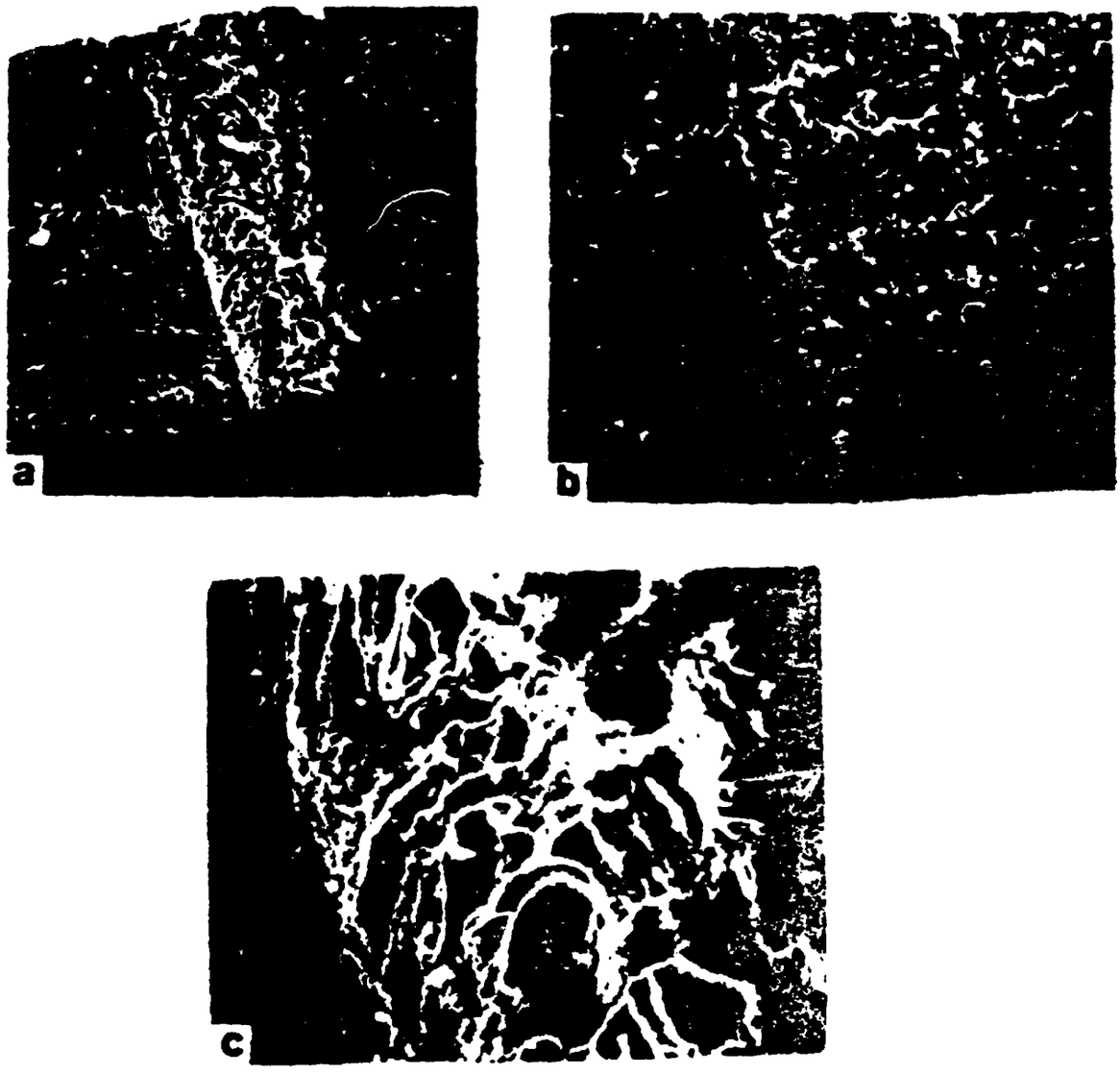

Figure 7.4. Polytetrafluoroethylene sample 10 mm long, after 40 flashovers. Alternating potential, flashover voltage 36 kV. a) Canal at electrode A, magnification 50 X, b) Canal at electrode B, magnification 50 X, c) Part of the canal from Figure 7.4a, magnification 200 X

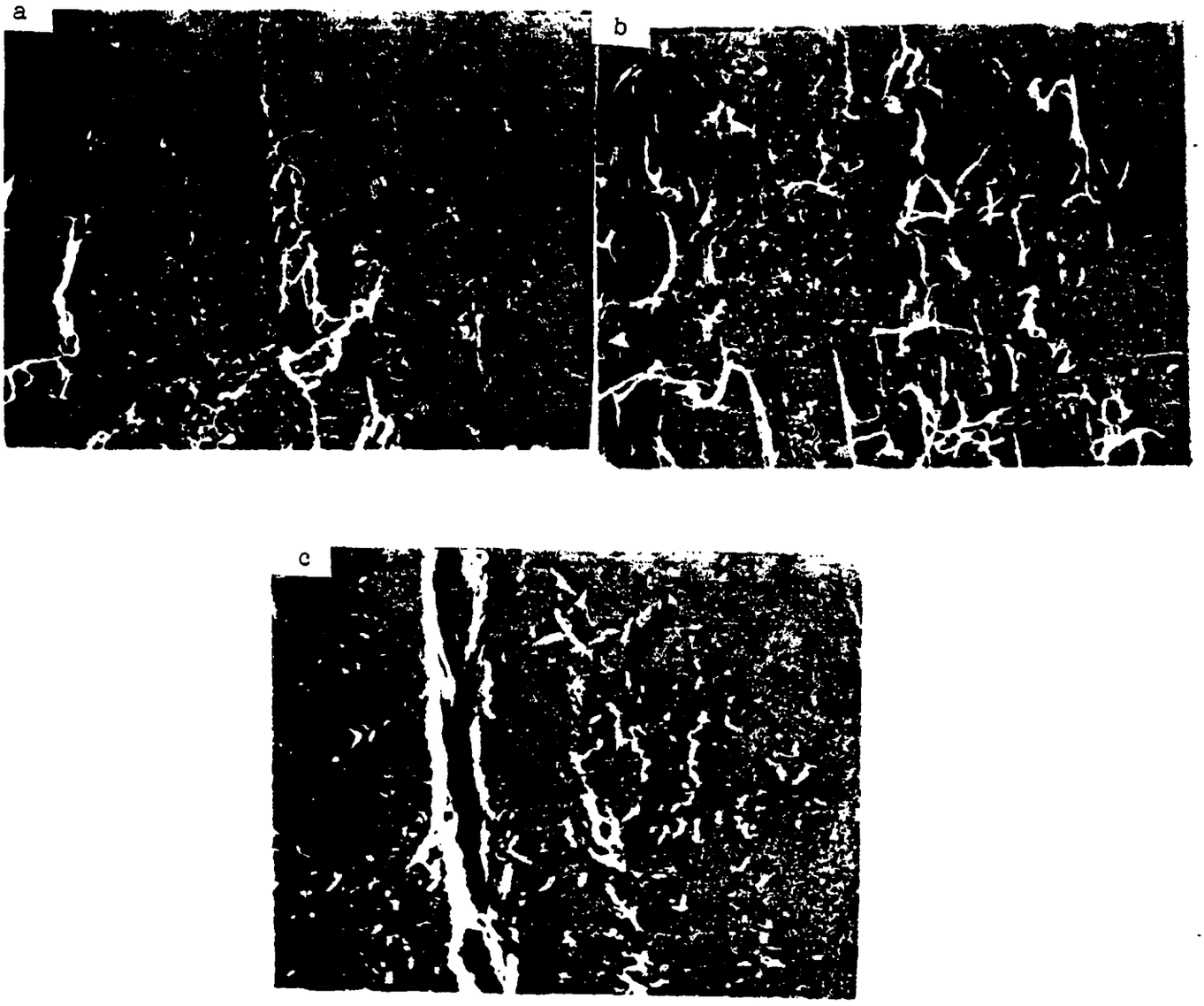

Figure 7.5. Polyethylene sample 10 mm long after 40 flashovers. Flashover voltage 30 kV, alternating potential.
a) Canal 1, middle part - magnification 100 X;
b) Canal 1, at electrode - magnification 100 X;
c) Canal 2, middle part - magnification 400 X

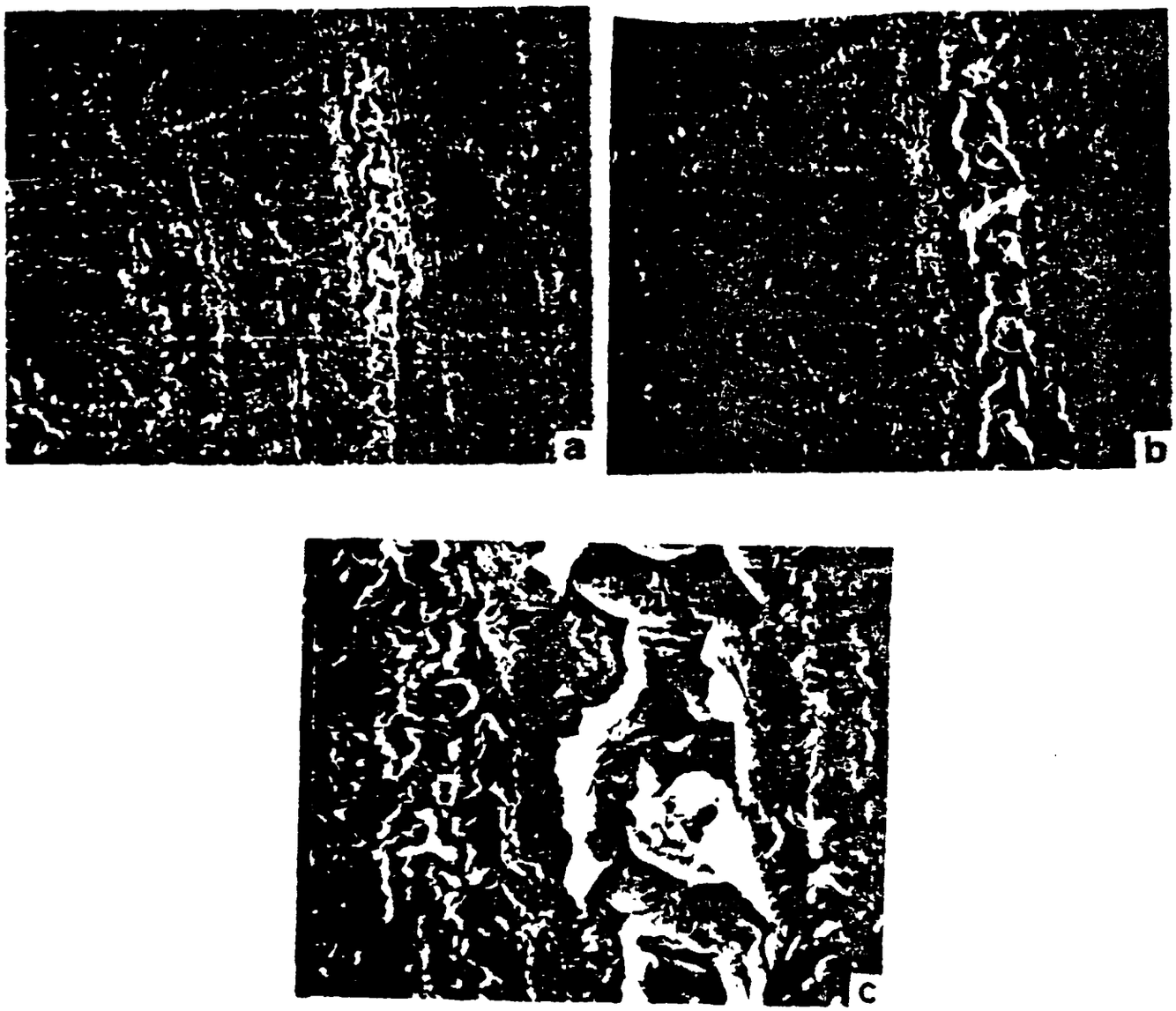

Figure 7.6. Polyethylene sample 10 mm long, after 40 flashovers. Flashover voltage 30 kV, alternating potential. Canal appearing on a part of the surface of sample: a) magnification 100 X, b) magnification 200 X, c) magnification 700 X

side canal 1, where the surface damaged by electric arc in vacuum shows the development of discharge along the broken line. This fact has affected the state of the surface of solid dielectric.

For samples of polytetrafluoroethylene and polyethylene several discharge canals were present on sample circumference after 40 flashovers in vacuum, similarly to the sample from polymethylmethacrylate.

Figure 7.4 shows one of characteristic discharge canals for a sample from polytetrafluoroethylene. The canal at electrode A is relatively narrow and deep in comparison with the same canal at electrode B, where discharge takes place on the surface of the solid dielectric causing damage to a larger area but to a considerably smaller depth. Transition of the canal from the form in Figure 7.4a to form in Figure 7.4b proceeds gradually. Figure 7.4c, which is a magnification of a part of Figure 7.4a, shows that the canal digs deeper into polytetrafluoroethylene. Each discharge causes not only desorption of gas, but also strong evolution of gas caused by decomposition of solid dielectric in the canal of electric arc.

Samples from polyethylene were also characterized by several discharge canals after 40 flashovers. For illustration, Figure 7.5 shows two discharge canals along polyethylene sample. Discharge canal 1 caused degradation of sample on a large area but the groove is not deep. On the other hand, in canal 2 there was a severe degradation of polyethylene in the form of considerably deeper and narrower groove in the sample.

The first three photographs in previously shown Figure 7.2 show local pre-flashover discharges on the surface of solid dielectric, which did not lead to flashover. A confirmation of the occurrance of such discharges are traces (marks) on surface of polyethylene (Figure 7.6). Degradation of a part of the surface of polyethylene in the form of point marks indicates that, in this case, electric arc consisted of several short arcs. Marks on the

surface of polyethylene resembled craters (spots) on electrodes and are the result of the point melting of polyethylene. The shape of these craters is very characteristic, corresponding to high temperature at the point of melting of arc. Traces in the middle part of the section of polyethylene surface are much larger. Similarly as in Figure 7.3 a broader belt of degradation of solid dielectric appeared in the middle part of the sample.

With the aid of photographs of discharges shown in Figure 7.2 and taking into consideration microscopic studies which showed the appearance of paths also in the middle part of the sample (Figure 7.6), one can explain the important role and effect of conditioning factors with direct and alternating potential. Conditioning with alternating potential causes an increase of the surface strength of system in relation to the surface strength after conditioning with direct potential because of the fact that at alternating potential the pre-flashover discharges develop more uniformly around the whole solid dielectric.

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Pre-flashover discharges developing around the whole thermoplastic solid dielectric liberate gas adsorbed by the surface of dielectric, and thus result in the occurrence of flashover in the layer of desorbed gas.

Considering studies of the mechanism of flashover that have been done so far and our investigations, the author of this work, similarly to others (Chapter 3), is of the opinion that electrons emitted from the surface of metal electrode (cathode) or which appeared at the dielectric-electrode-vacuum junction as a result of ionization bombard the surface of solid dielectric causing the charging of the surface of the solid dielectric with a positive charge (Figure 7.7). This charging of the surface of solid dielectric with a positive charge results from the secondary emission of electrons on the surface of solid dielectric.

Colliding with the surface of solid dielectric, electrons

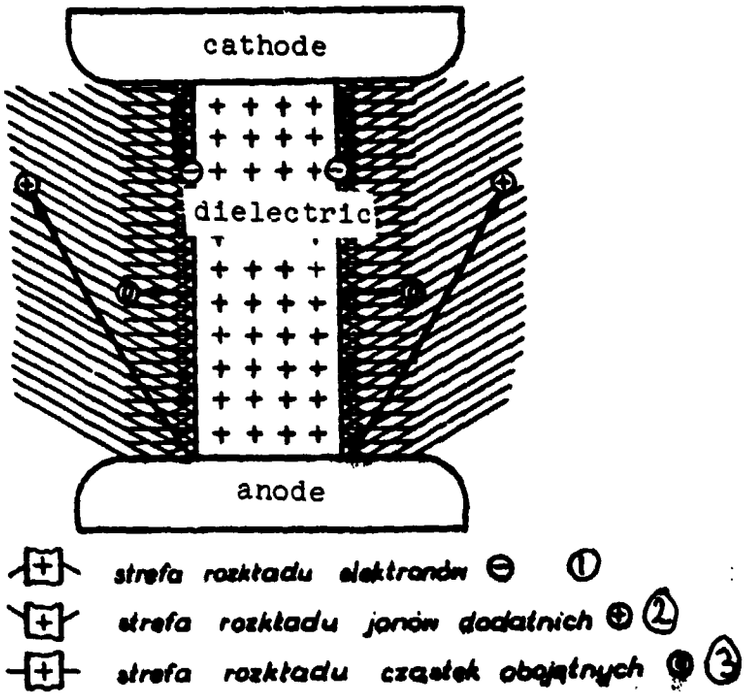

Figure 4.7. Distribution of electric charges in the system with solid dielectric in vacuum
1 - area of distribution of electrons
2 - area of distribution of positive ions
3 - area of distribution of neutral particles

cause evolution of gas from the surface of dielectric, which means at the same time liberation of neutral particles which move in parallel to equipotential surfaces forming a space with predominance of neutral particles.

Colliding with the surface of electrode (anode), electrons cause liberation of positive ions (cations)from the anode. They

move slowly in the direction of cathode but at a larger distance from the surface of solid dielectric than the electrons, and they form space charge (Figure 7.7).

The dependence of flashover potential as a function of the time of duration of switching surge wave front is the sum of the action of surface charge, arising on the surface of solid dielectric as a result of secondary emission of electrons, of surface resistance of solid dielectric, and of the layer of gas desorbed around the dielectric.

As the time of duration of switching surge wave front increases, the charge accumulating on the surface of solid dielectric becomes larger and larger, and its effect on the lowering of surface strength also becomes larger. At the same time, with increase of the time of wave front there is an increase of the amount of desorbed gas forming a thin gas sheath around the solid dielectric. Electrical discharges develop in this gas sheath. With an increase of the amount of desorbed gas there is a lowering of flashover voltage.

But gas layer enables the transfer of a part of the surface charge to the gas layer, causing a reduction of the density of charge on the surface of dielectric. Moreover, the gas layer reduces surface resistance of solid dielectric, enabling a part of the surface charge to drai. off. These factors cause an increase of surface strength as a function of the time of duration of switching surge wave front. The role of surface charge and surface resistance of solid dielectric, according to Equation (5.2), was shown previously in Figure 5.24.

The author does not know any other work which explains the mechanism of fl sh ver along surfaces of solid dielectric at switching surge potential in this way. The above given machanism of flashover can be also extended to other impulse potentials.

8. FINAL CONCLUSIONS

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The ever increasing application of vacuum as an insulation medium in electroenergetic facilities creates the need of closer knowledge of the electrical surface strength of solid dielectrics in vacuum at surge and switching surge overvoltages. The aim of the author was to supplement the range of investigations in this area. This work contains results of studies of electrical surface strength of solid dielectrics in vacuum, and explains the mechanism of flashover at switching surge overvoltages.

In summing up the results of studies, the author wishes to point out these aspects of the work which bring a new contribution and in significant way broaden the actual state of knowledge in the area of electrical surface strength of solid dielectrics in vacuum. The most important achievements of this work include:

1. Finding a dependence of the electrical surface strength of solid dielectric in vacuum on the time of duration of switching surge wave front.
2. Determining a mathematical relation describing the mechanism of flashover at switching surges.
3. Advancing a physical interpretation of the mechanism of flashover along solid dielectrics in vacuum at switching surges.
4. Describing an increase of flashover voltage along investigated solid dielectrics at direct and surge potentials approximately by square root of the length of the sample.
5. Finding, by means of microscopic studies, the formation of permanent canals on the surface of solid dielectric which cause lowering of surface strength. The shape of canals is dependent on the type of insulating material.
6. Finding that thermoplastic materials suffer relatively fast degradation, and after 30-35 flashovers the investigated sample looses practically all surface strength.

7. Establishing that the investigated thermoplastic materials may be put in the following order with respect to their surface strength and the degree of resistance to degradation of surface of dielectric under the action of flashovers:
   - polymethylmethacrylate,
   - polytetrafluoroethylene,
   - polyethylene.
8. Finding that surface strength depends very strongly on the method of conditioning of the sample: the type of conditioning potential, number of conditioning flashovers, value of conditioning voltage, and the type of test potential.

The author hopes that the presented results of studies and the proposed mechanism of flashover along solid dielectric in vacuum at surge and switching overvoltages will find practical application in planning and use of electroenergetic vacuum facilities, and will be utilized for further scientific studies of the properties of vacuum systems under conditions of electrical discharges.

9. APPENDICES

Appendix 1. Flashover potential for polytetrafluoroethylene with conditioning at direct and alternating potentials.

Rodzaj kondycjonowania (1)	Rodzaj napięcia probierczego (2)	Napięcie przeskoku w kV (3)			
		Długość próbki (4) 5 mm	10 mm	15 mm	20 mm
Napięcie przemienne (5)	udarowe 1,2/50 µs (7)	60,0	84,3	108,0	127,0
	stałe (8)	45,7	70,5	86,2	100,2
	przemienne (9)	29,5	40,0	47,6	53,8
Napięcie stałe (6)	stałe (8)	43,8	62,9	77,1	90,0
	udarowe 1,2/50 µs (7)	37,6	55,7	65,2	70,0
	przemienne (9)	21,9	26,7	30,5	32,4

Key: (1) Type of conditioning; (2) Type of test potential; (3) Flashover potential in kV; (4) Length of sample; (5) Alternating potential; (6) Direct potential; (7) Surge 1.2/50 µs; (8) Direct; (9) Alternating.

Appendix 2. Flashover voltage for polymethylmethacrylate at various types of potential. Conditioning with direct potential.

Rodzaj napięcia (1)	Zmierzone napięcie przeskoku w kV (2)				Uzyskany wzór odzwierciedlający napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
stałe (6)	41,0	65,2	81,0	92,9	$U_p = 16{,}057\ d^{0{,}594}$	41,7	63,1	80,2	95,2
udarowe 1,2/50 µs (7)	36,2	60,5	73,3	84,3	$U_p = 13{,}953\ d^{0{,}611}$	37,3	57,0	73,0	87,1
przemienne (8)	24,7	35,7	42,4	48,6	$U_p = 11{,}399\ d^{0{,}486}$	24,9	34,9	42,6	48,9
udar łącz. 35/80 µs (9)	31,3	50,8	66,4	77,3	$U_p = 10{,}959\ d^{0{,}659}$	31,6	50,0	65,3	78,9
udar łącz. 50/250 µs (10)	26,6	43,0	57,0	71,9	$U_p = 8{,}410\ d^{0{,}712}$	26,4	43,3	57,8	70,9
udar łącz. 80/700 µs (11)	23,4	35,9	48,4	57,0	$U_p = 8{,}182\ d^{0{,}650}$	23,3	36,5	47,5	57,3
udar łączeniowy 150/1800 µs (12)	27,3	41,4	46,9	51,6	$U_p = 13{,}448\ d^{0{,}460}$	28,2	38,8	46,7	53,4
udar łączeniowy 400/2000 µs (13)	31,3	46,1	54,7	58,6	$U_p = 15{,}249\ d^{0{,}463}$	32,1	44,3	53,4	61,0
udar łączeniowy 600/3000 µs (14)	32,8	50,8	60,9	65,6	$U_p = 14{,}870\ d^{0{,}511}$	33,8	48,2	59,3	68,7

Key: (1) Type of ptential; (2) Measured flashover potential in kV; (3) Length of sample; (4) Equation representing the flashover potential; (5) Flashover potential calculated from equation; (6) Direct; (7) Surge (impulse) 1.2/50 µs, (8) Alternating; (9-14) Switching surge.

Appendix 3. Flashover voltage for polymethylmethacrylate, polytetrafluoroethylene and polyethylene. Conditioning with direct potential.

Rodzaj dielektryku (1)	Rodzaj napięcia przebiorczego (2)	Zmierzone napięcie przeskoku w kV (3)				Uzyskany wzór odzwierciedlający napięcie przeskoku (5)	Obliczone napięcie przeskoku wg wzoru (6)			
		Długość próbki (4)					Długość próbki (4)			
		5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
polimetakrylan metylu (7)	stałe (10)	41,0	63,2	81,0	92,9	$U_p = 16,057\ d^{0,594}$	41,7	63,1	80,2	95,2
	udarowe 1,2/50 µs (11)	36,2	60,5	75,3	84,3	$U_p = 13,953\ d^{0,611}$	37,3	57,0	73,0	87,1
	przemienne (12)	24,7	35,7	42,4	48,6	$U_p = 11,399\ d^{0,486}$	24,9	34,9	42,6	48,9
politetrafluoroetylen (8)	stałe (10)	43,8	62,9	77,1	90,0	$U_p = 19,042\ d^{0,518}$	45,8	62,7	77,4	89,8
	udarowe 1,2/50 µs (11)	57,6	55,7	65,2	70,0	$U_p = 18,540\ d^{0,457}$	58,7	53,0	63,9	72,8
	przemienne (12)	21,9	26,7	30,5	32,4	$U_p = 13,791\ d^{0,288}$	21,9	26,7	30,1	32,7
polietylen (9)	stałe (10)	59,5	60,0	70,5	79,0	$U_p = 18,043\ d^{0,502}$	40,4	57,3	70,2	81,1
	udarowe 1,2/50 µs (11)	33,8	48,6	57,6	63,8	$U_p = 16,3?5\ d^{0,462}$	34,3	47,3	57,0	65,1
	przemienne (12)	20,5	24,3	27,5	30,0	$U_p = 13,073\ d^{0,275}$	20,4	24,6	27,6	29,8

Key: (1) Type of dielectric; (2) Type of test potential; (3) Measured flashover potential in kV; (4) Length of sample; (5) Equation representing the flashover potential; (6) Flashover potential calculated from equation; (7) Polymethylmethacrylate; (8) Polytetrafluoroethylene; (9) Polyethylene; (10) Direct; (11) Surge 1.2/50 µs; (12) Alternating.

Appendix 4. Flashover voltage for polymethylmethacrylate, polytetrafluoroethylene and polyethylene. Conditioning with alternating potential.

Rodzaj dielektryku (1)	Rodzaj napięcia probierczego (2)	Pomierzone napięcie przeskoku w kV (3) — Długość próbki (4) 5 mm	10 mm	15 mm	20 mm	Uzyskany wzór odwzorowujący napięcie przeskoku (5)	Obliczone napięcie przeskoku wg wzoru (6) — Długość próbki (4) 5 mm	10 mm	15 mm	20 mm
polimetakrylan metylu (7)	udarowe 1,2/50 µs (10)	62,4	90,5	113,0	134,0	$U_p = 25{,}697\ d^{0{,}549}$	62,17	90,96	113,6	133,1
	stałe (11)	49,5	73,3	88,6	106,0	$U_p = 20{,}751\ d^{0{,}542}$	49,6	72,3	90,1	105,3
	przemienne (12)	37,6	49,0	64,3	74,3	$U_p = 16{,}472\ d^{0{,}497}$	36,7	51,7	63,4	73,1
politetrafluoroetylen (8)	udarowe 1,2/50 µs (10)	60,0	84,3	108,0	127,0	$U_p = 24{,}778\ d^{0{,}542}$	59,3	86,3	107,6	125,8
	stałe (11)	45,7	70,5	86,2	100,2	$U_p = 18{,}610\ d^{0{,}565}$	46,3	68,6	86,2	101,4
	przemienne (12)	29,5	40,0	47,6	53,8	$U_p = 14{,}751\ d^{0{,}431}$	29,5	39,8	47,4	53,7
polietylen (9)	udarowe 1,2/50 µs (10)	58,6	84,3	104,0	116,4	$U_p = 26{,}436\ d^{0{,}459}$	59,0	83,5	102,3	118,0
	stałe (11)	44,3	64,3	81,0	93,8	$U_p = 18{,}450\ d^{0{,}544}$	44,3	64,3	80,5	94,1
	przemienne (12)	27,1	36,7	43,8	48,6	$U_p = 13{,}727\ d^{0{,}425}$	27,2	36,5	43,4	49,0

Key: (1) Type of dielectric; (2) Type of test potential; (3) Measured flashover potential in kV; (4) Length of sample; (5) Equation representing the flashover potential; (6) Flashover potential calculated from equation; (7) Polymethylmethacrylate; (8) Polytetrafluoroethylene; (9) polyethylene; (10) Surge 1.2/50 µs, (11) Direct; (12) Alternating.

Appendix 5. Flashover voltage for polytetraflyoroethylene at various types of potential. Conditions with direct potential.

Rodzaj napięcia (1)	Zmierzone napięcie przeskoku w kV (2)				Wyznaczony wzór odzwierciedlający napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
stałe (6)	43,8	62,9	77,1	90,0	$U_p = 19{,}042\ d^{0{,}518}$	43,8	62,7	77,4	89,8
udarowe 1,2/50 μs (7)	37,6	55,7	65,2	70,0	$U_p = 18{,}540\ d^{0{,}457}$	38,7	53,0	63,9	72,8
przemienne (8)	21,9	26,7	30,5	32,4	$U_p = 13{,}791\ d^{0{,}288}$	21,9	26,7	30,1	32,7
udar łącz. 35/80 μs (9)	27,3	43,8	57,8	64,8	$U_p = 9{,}924\ d^{0{,}638}$	27,7	43,1	55,8	67,1
udar łącz. 50/250 μs (10)	23,4	37,5	50,0	60,2	$U_p = 7{,}774\ d^{0{,}685}$	23,4	37,6	47,6	60,6
udar łącz. 60/700 μs (11)	21,9	32,0	44,5	51,6	$U_p = 7{,}810\ d^{0{,}631}$	21,0	33,4	43,1	51,7
udar łączeniowy 150/1800 μs (12)	26,3	32,0	43,2	46,9	$U_p = 12{,}787\ d^{0{,}432}$	25,6	34,5	41,1	46,6
udar łączeniowy 400/2000 μs (13)	25,8	35,2	49,2	54,7	$U_p = 10{,}235\ d^{0{,}562}$	25,3	37,4	46,9	55,1
udar łączeniowy 400/3000 μs (14)	27,3	36,7	51,6	58,6	$U_p = 10{,}654\ d^{0{,}568}$	26,6	39,4	49,6	58,4

Key: (1) Type of potential; (2) Measured flashover potential in kV; (3) Length of sample; (4) Equation representing the flashover potential; (5) Flashover potential calculated from equation; (6) Direct; (7) Surge 1.2/50 us; (8) Alternating; (9-14) Switching surge.

Appendix 6. Flashover voltage for polyethylene at various types of potentials. Conditioning with direct potential

Rodzaj napięcia (1)	Pomierzone napięcie przeskoku w kV (2)				Uzyskany wzór odzwierciedlający napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
stałe (6)	39,5	60,0	70,5	79,0	$U_p = 18{,}043\ d^{0{,}502}$	40,4	57,3	70,2	81,1
udarowe 1,2/50 µs (7)	33,8	48,6	57,6	65,8	$U_p = 16{,}313\ d^{0{,}462}$	34,3	47,3	57,0	65,1
przemienne (8)	20,5	24,3	27,5	30,0	$U_p = 13{,}073\ d^{0{,}275}$	20,4	24,6	27,6	29,8
udar łącz. 35/80 µs (9)	25,0	40,6	50,0	57,8	$U_p = 9{,}629\ d^{0{,}606}$	25,5	38,9	49,8	59,2
udar łącz. 50/250 µs (10)	22,7	33,6	46,9	53,1	$U_p = 8{,}150\ d^{0{,}631}$	22,5	34,8	45,0	53,9
udar łącz. 80/700 µs (11)	19,5	26,6	36,7	47,7	$U_p = 6{,}68\ d^{0{,}630}$	18,6	28,9	37,5	45,0
udar łącz.150/1800 µs (12)	20,0	28,9	37,5	44,5	$U_p = 7{,}802\ d^{0{,}578}$	19,8	29,5	37,4	44,1
udar łącz.400/2000 µs (13)	24,2	34,4	42,2	48,4	$U_p = 10{,}818\ d^{0{,}501}$	24,2	34,3	42,1	48,6
udar łącz.600/3000 µs (14)	27,3	35,9	43,8	53,9	$U_p = 12{,}352\ d^{0{,}478}$	26,7	37,1	45,1	51,8

Key: 1 - Type of potential, 2 - Measured flashover potential in kV, 3 - Length of sample, 4 - Equation representing the flashover potential, 5 - Flashover potential calculated from equation, 6 - direct, 7 - surge 1.2/50 µs, 8 - alternating, 9-14 - switching surge

Appendix 7. Flashover voltage for polymethylmethasrylate at various types of potentials. Conditioning with alternating potential.

Rodzaj napięcia (1)	Zmierzone napięcie przeskoku w kV (2)				Używany wzór odwzorowujący napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
udarowe 1,2/50 μs (6)	62,4	90,5	113,0	134,0	$U_p = 25,697\ d^{0,549}$	62,17	90,96	113,6	133,1
stałe (7)	49,5	73,3	88,6	106,0	$U_p = 20,751\ d^{0,542}$	49,6	72,3	90,1	105,3
przemienne (8)	37,6	49,0	64,3	79,3	$U_p = 16,472\ d^{0,497}$	36,7	51,7	63,4	73,1
udar łąc. 35/80 μs (9)	60,0	85,3	105,0	122,2	$U_p = 27,740\ d^{0,501}$	62,1	87,9	107,4	124,4
udar łąc. 50/250 μs (10)	57,2	82,2	103,6	120,0	$U_p = 24,099\ d^{0,535}$	57,1	82,7	102,7	119,9
udar łąc. 80/700 μs (11)	53,3	75,9	100,4	112,3	$U_p = 21,935\ d^{0,549}$	53,1	77,6	96,9	113,5
udar łąc. 150/1800 μs (12)	51,7	74,4	90,8	108,0	$U_p = 22,129\ d^{0,526}$	51,6	74,3	92,0	107,0
udar łąc. 400/2000 μs (13)	54,1	76,7	93,1	114,0	$U_p = 22,979\ d^{0,526}$	53,6	77,2	95,6	111,2
udar łąc. 600/3000 μs (14)	55,6	79,0	96,3	119,2	$U_p = 23,189\ d^{0,536}$	55,0	79,8	99,2	115,7

1 - Type of potential, 2 - Measured flashover potential in kV, 3 - Length of sample, 4 - Equation representing the flashover potential, 5 - Flashover potential calculated from equation, 6 - surge 1.2/50 μs, 7 - direct, 8 - alternating, 9-14 - switching surge

Appendix 8. Flachover voltage for polytetrafluoroethylene at variuus types of potentials. Conditioning with alternating potential.

Rodzaj napięcia (1)	Pomierzone napięcie przeskoku w kV (2)				Usyskany wzór odzwierciedlający napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
udarowe 1,2/50 µs	60,0	84,3	108,0	127,0	$U_p = 24{,}778\ d^{0{,}542}$	59,3	86,3	107,6	125,8
stałe (7)	45,7	70,5	86,3	100,2	$U_p = 18{,}610\ d^{0{,}565}$	46,3	68,6	86,2	101,4
przemienne (8)	29,5	40,0	47,6	53,8	$U_p = 14{,}751\ d^{0{,}431}$	29,5	39,8	47,4	53,7
(6) udar łącz. 35/80 µs	57,2	83,8	97,0	122,4	$U_p = 24{,}514\ d^{0{,}526}$	57,1	82,3	101,8	118,5
(9) udar łącz. 50/250 µs	54,8	73,6	95,5	118,2	$U_p = 22{,}053\ d^{0{,}547}$	53,2	77,7	96,9	113,5
(10) udar łącz. 80/700 µs	50,2	68,1	93,1	112,5	$U_p = 19{,}037\ d^{0{,}583}$	48,6	72,8	92,2	109,1
(11) udar łącz. 150/1800 µs	50,7	71,3	91,6	107,6	$U_p = 20{,}565\ d^{0{,}549}$	49,8	72,8	90,9	106,5
(12) udar łącz. 400/2000 µs	50,2	72,8	92,6	112,0	$U_p = 19{,}786\ d^{0{,}572}$	49,7	73,8	93,1	109,8
(13) udar łącz. 600/3000 µs	50,9	73,4	93,3	115,0	$U_p = 19{,}795\ d^{0{,}578}$	50,2	74,8	94,6	111,7

1 - Type of potential, 2 - Measured flashover potential in kV, 3 - Length of sample, 4 - Equation representing the flashover potential, 5 - Flashover potential calculated from equation, 6 - surge 1.2/50 µs, 7 - direct, 8 - alternating, 9-14 - switching surge

Appendix 9. Flashover voltage for polyethylene at various types of potentials. Conditioning with alternating potential.

Rodzaj napięcia (1)	Zmierzone napięcie przeskoku w kV (2)				Uzyskany wzór odwzorowujący napięcie przeskoku (4)	Obliczone napięcie przeskoku wg wzoru (5)			
	Długość próbki (3)					Długość próbki (3)			
	5 mm	10 mm	15 mm	20 mm		5 mm	10 mm	15 mm	20 mm
udarowe 1,2/50 µs	58,6	84,3	104,0	116,4	$U_p = 26{,}436\ d^{0{,}459}$	59,0	83,5	102,3	118,0
stałe (7)	44,3	64,3	81,0	93,8	$U_p = 18{,}450\ d^{0{,}544}$	44,3	64,5	80,5	94,1
przemienne (8)	27,1	36,7	43,8	48,6	$U_p = 13{,}727\ d^{0{,}425}$	27,2	36,5	43,4	49,0
(9) udar łącz. 35/80 µs	54,8	76,0	95,5	112,4	$U_p = 23{,}667\ d^{0{,}513}$	54,3	77,5	95,5	110,8
(10) udar łącz. 50/250 µs	51,7	71,3	93,1	106,5	$U_p = 21{,}887\ d^{0{,}527}$	51,1	73,6	91,1	106,1
(11) udar łącz. 80/700 µs	46,3	57,3	86,9	101,7	$U_p = 17{,}130\ d^{0{,}582}$	43,7	65,5	82,9	98,1
(12) udar łącz.150/1800 µs	46,3	66,6	82,2	97,8	$U_p = 19{,}491\ d^{0{,}537}$	46,1	66,8	83,0	96,8
(13) udar łącz.400/2000 µs	49,4	70,5	96,1	104,1	$U_p = 20{,}001\ d^{0{,}560}$	49,2	72,6	91,2	197,0
(14) udar łącz.600/3000 µs	50,9	73,6	90,2	106,0	$U_p = 21{,}846\ d^{0{,}526}$	50,9	73,3	90,7	105,5

1 - Type of potential, 2 - Measured flashover potential in kV, 3 - Length of sample, 4 - Equation representing the flashover potential, 5 - Flashover potential calculated from equation, 6 - surge 1.2/50 µs, 7 - direct, 8 - alternating, 9-14 - switching surge

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SURFACE ELECTRIC STRENGTH OF THERMOPLASTIC MATERIALS IN VACUUM

S u m m a r y

Despite the wide application of vacuum and the numerous studies presented in this domain, there is no, till now, the generally accepted theory explaining the flashover mechanism along the solid dielectric in vacuum. This work classify and analyse the influence of various elements on the flashover mechanism and on the electric strength of vacuum-solid dielectric system. In particular the influence of pressure, sample length, metallization of electrode - sample contact surfaces and conditioning factors is presented on the basis of the author experiments.

The experimental results of surface electric strength of thermoplastic materials (polymethyl methacrylate, polytetrafluoroethylen, polyethylene) submitted to switching and surge overvoltages are given and analysed in relation to the switching surge number and its wave front duration. The theory of the flashover mechanism along the investigated materials in vacuum, elaborated by the author, is presented and the analytical expression for flashover voltage as the function of switching surge wave front duration is given.

The investigation of flashover mechanism was completed by the measurement of solid dielectrics surface degradation rate. The analysis of succeeding switching surges development in oscillograph records is presented together with the pictures of solid dielectric distroyed surfaces after flashovers at d.c. or a.c. voltage taken by electron microscope.